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A GPSS II SIMULATION MODEL TO EVALUATE TERRAIN CAPABILITIES OF TYPICAL PULPWOOD HARVESTING VEHICLES

A THESIS

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CAPABILITIES OF TYPICAL PULPWOOD HARVESTING VEHICLES

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SUMMARY

A major problem facing the pulpwood producer is the purchasing of harvesting equipment with appropriate operating options. In view of increasing equipment costs the producer cannot afford mistakes in equipment selection.

The objective of this thesis is to provide the pulpwood producer with a means to evaluate typical pulpwood harvesting vehicles prior to purchase, in relation to their performance in various different terrain conditions.

To accomplish this objective a digital computer simulation model is used to simulate the movement of a typical pulpwood harvesting vehicle across the terrain to be encountered in five pulpwood resource areas within Georgia. General Purpose Systems Simulator II is the simulation language employed in order that the model may be as clear as possible to those individuals unfamiliar with simulation techniques.

In order to construct the computer simulation model, it is necessary to conduct a thorough literature search to determine vehicle mobility characteristics which define a vehicle's ability to negotiate terrain. Likewise the qualities of terrain must be defined in quantitative terms so that interaction between the vehicle and the terrain can be described. It was determined that no widely acknowledged method exists to accomplish the above. The researcher selected the U. S. Army Corps of Engineers Waterways Experiment Station's method of defining terrain and vehicle mobility and added refinements.

The results of the computer simulation show the percentage of the resource areas that the vehicle can negotiate prior to being halted. An analysis of variance is conducted to determine if there is a significant difference in trafficability among the five resource areas and if changing the tire size of the vehicle modelled results in a significant difference in vehicle performance.

The conclusions reached by the researcher are primarily that the simulation model does evaluate a vehicle, that differences do exist between the areas modelled and also that vehicle performance does vary with different tire sizes.

Further research is proposed to provide additional analysis of areas other than those modelled.

CHAPTER I

INTRODUCTION

Purpose

The rapidly rising costs of producing pulpwood harvesting equipment have reached the point where neither the pulpwood producer nor the equipment manufacturer can afford mistakes in equipment capabilities. The Melroe Bobcat 500 Loader costs $5,200 (1) and is a very small and basic vehicle. A major item of equipment, such as the 21-inch Nicholson Utilizer, costs $198,000 (2). As labor cost increases, the present trend is towards more productive and more efficient harvesting machines.

The high costs involved in these major items of equipment demand that the vehicle be objectively evaluated before purchase by the harvester and before tooling and production by the manufacturer. Part of this evaluation requires determination of the ability of the equipment to perform its task across the varying types of terrain to be encountered in pulpwood resource areas. In an ideal situation, the prospective purchaser would like to know that a specific machine has a probability X of operating over Y percentage of his total resource areas.

It is the purpose of this thesis to develop a valid vehicular model that will enable the vehicle to be evaluated on its ability to negotiate terrain. This evaluation is to be based primarily on assumed statistical distributions of the ability of the ground to withstand vehicular movement, variations in slope and ground roughness, and the vegetation that restricts vehicular movement. The mobility model illustrates those critical vehicle characteristics which determine mobility and how slight changes in vehicle design can bring significant changes in performance.

It is expected that this approach will provide the pulpwood harvester with a means whereby he can select the item of equipment most suitable to the terrain to be encountered in his particular pulpwood resource areas. It is further expected that the producer will through use of this analytical technique, be able to project a dollar value on the benefits to be derived from equipment modification.

Background

The problem of ground mobility has existed since animals first walked on the face of the earth. As man learned that he was not totally committed to walking and carrying loads on his back, he began to devise substitutes for the rather exhausting process of do-it-yourself transportation. The stories of the development of the wheel and the ship are well known. When man began designing ships, he discovered that building a ship is a rather lengthy process at best. Mistakes in design did not result in a mere inconvenience but wasted considerable time and money. To avoid this waste, man began to apply scientific methods to ship design. The result was that the major factors constituting a ship's performance could be basically determined prior to actual construction.

The advent of aircraft carried with it the element of considerable risk to life in addition to money. Hence, aircraft design principles were also based on scientific methods. As aircraft became larger and carried increased loads, additional demands were made upon the scientist to determine aircraft performance prior to actual construction. A classic case of these scientific methods being applied to aircraft was the 1941 development of the North American P-51 Mustang (3). This aircraft's performance was fully predicted prior to manufacture. The time from beginning of design to production was minimal due to the ability to predict what the design would do before it was constructed. Today even that prediction of performance is not sufficient and modern aircraft are thoroughly "war-gamed" to determine their "cost-effectiveness" prior to production.

Because of the limited costs involved in producing ground vehicles in the past, it has been possible to design ground vehicles on a trial and error basis. As Dr. M. G. Bekker stated:

> Unfortunately, the modern development of off-the-road vehicles has been somewhat overshadowed by other undoubtedly more spectacular means of transportation; in general, existing equipment has been modified empirically and there has been no attempt to develop basic principles of the mechanics of land locomotion (4).

Likewise, in evaluating possible vehicle designs, the art of determining "cost-effectiveness" is still in its infancy. A Rand Corporation Study has indicated that the majority of cost-effectiveness determinations are, at present, subjective type judgements (5).

World War II demonstrated the need for the ability to predict vehicle performance. The British Army enjoyed a high degree of success in North Africa as regards the mobility of their vehicles. They received a considerable shock in the invasion of Europe when the same vehicles could not perform with an equal degree of efficiency (6). To prevent further occurrences of such surprises, the United States, Great Britain, and Canada began to appreciate the need to define the terrain-vehicle relationship.

Within the United States, the task initially fell to the United States Army Corps of Engineers Waterways Experiment Station. Their initial task was to develop a method whereby the supportive capacity of terrain could be determined. In 1956, the Waterways Experiment Station published a technique which was based on empirical data obtained from cone penetrometer readings and vehicle tests. The Waterways Experiment Station further attempted to quantitatively define terrain for mobility purposes and published this method in a series of papers in 1968 (7). The method itself is concisely explained by Shamburger in "A Quantitative Method for Describing Terrain for Ground Mobility" (8). Other areas that have concerned the Waterways Experiment Station include experimentation with other methods of quantifying mobility and terrain.

The Land Locomotion Laboratory of the United States Army Tank Automotive Center has also been working on the problems of ground mobility since World War II. The approach used by the Land Locomotion Laboratory was somewhat different from that used by the Waterways Experiment Station. The studies conducted by the Land Locomotion Laboratory were more theoretical and were primarily concerned with the relationship between the vehicle and the soil in which it operates.

Theory of Land Locomotion, written by Bekker (9) in 1956, examines this relationship in depth. The basis of this approach was the amount of sinkage of a wheel or track into soil. From this sinkage, rolling resistance and tractive effort were determined. The work of the Land Locomotion Laboratory through 1966 is summarized in its *Research Report No. 6* (10).

In Canada, the problem of ground mobility has been primarily the responsibility of the Canadian Armament Research and Development Establishment although considerable work has also been performed by the Muskeg Research Council presently operating under the National Research Council. Canada, with its vast acreages of marginal terrain, is vitally interested in ground mobility. The Canadians have resorted to a semi-empirical approach which was published as "A Rational Empirical Approach to Muskeg Vehicle Research" (11). The Canadians, with whom Bekker began work following World War II, used certain aspects of the load sinkage equation to develop their drawbar-pull/weight ratio as a measure of mobility. They recognized that maximum drawbar-pull may occur at 100 per cent slippage of the driving wheels and thus resorted to dimensional analysis of physical models to further define the relationship (12). One of the contributions of the Muskeg Research Council is the hypothesis of considerable random factors in the determination of mobility.

The areas of disagreement among the preceding agencies are numerous. No agreement presently exists regarding the determination of ground mobility. There are several flaws in each theory and these further contribute to the disagreement among agencies.

The Land Locomotion Laboratory conducted a series of experiments whereby the drawbar-pull/weight was used as the index of performance. These experiments indicated that the drawbar-pull/weight ratio was a rather insensitive measure of off-the-road vehicle performance. The dominant factors were the man-machine factors and included such things as the transmission, visibility, ride, comfort, and driver ability (13). The importance of the man-machine relationship was also indicated by the Muskeg Research Council in their work in addition to such qualitative items as visibility and ease of operation (14).

The inferences to be drawn from this background are as follows:

(1) that there is, at present, no widely acknowledged measure of vehicle mobility;

(2) that the man-machine relationship, unquantified at present, plays a major role in ground mobility; and

(3) that the terrain factors which determine ground mobility are not quantified in a manner acceptable to all concerned.

The Muskeg Research Council stated that ". . . the problem is enormously difficult because of the large number of significant variables of a stochastic nature and the very many variables" (15). In such a situation digital computer simulation offers a method of approach that might provide a much more realistic evaluation than has heretofore been experienced.

General Nature of the Problem

In order to clarify the following chapters for the reader, a general description of the nature of operations of pulpwood harvesting vehicles in their assigned tasks is in order.

A typical pulpwood harvesting vehicle is expected to perform assigned tasks within a particular pulpwood resource area. In this paper such area is described by samples of specific resource areas scattered throughout the state of Georgia. In practical application, the producer expects to operate within a reasonable radius from his base of operations. This base of operations may be a place where he does his hiring, where he stores and maintains his equipment, or merely where he lives. The harvester requires his equipment to be transportable within his area and capable of coping with the terrain conditions within the resource areas available to him.

The vehicle, within the resource area, is expected to be able to move to all harvestable trees. This requirement necessitates the ability to traverse soil, overcome obstacles, negotiate slopes, maneuver through existing vegetation, and traverse minor terrain obstacles, such as streams of the resource area.

Each vehicle has options provided by the manufacturer. The harvester, in purchasing his equipment, must determine which vehicle option combination will best fit his requirements. He relies upon his experience, knowledge, and the knowledge and reputation of the manufacturer in making his decision.

Study Objectives

From the description of the background and general nature of the problem, it can be seen that the number of parameters acting upon a design are considerable and the combinations thereof are of a magnitude sufficient to rule out the possibility of exploring every one. Likewise, the total number of possible combinations of terrain classifications is sufficiently large to preclude examination of all types. However, the alternatives open to the pulpwood harvester are limited to ordering slight options in equipment design or in selecting completely different equipment produced by another manufacturer. This equipment selection is based upon a knowledge of the area in which the harvester operates. The overall objective of this study is to determine which design best suits the harvester's area and what options affecting mobility are most desirable.

The specific objectives of this study in the order of their investigation are:

1. Select or formulate a system that adequately describes quantitatively the terrain-vehicle relationship within the limitations imposed hereafter.

2. Construct a digital computer simulation model of the system using a GPSS II simulation language.

3. Utilize the computer model to simulate a typical pulpwood harvesting vehicle and the terrain it is expected to traverse.

4. From the resultant data, specify the percentage of selected pulpwood resource areas which the vehicle can be expected to harvest with a high probability of success.

5. Indicate if the terrain is too difficult for the harvesting vehicle selected regardless of tire size.

These objectives will be accomplished by testing the following hypothesis:

(1) that there are no significant differences in the pulpwood resource areas under examination;

(2) that there is no significant difference in vehicle performance when equipped with two different tire sizes.

Scope and Limitations

In view of the large number of parameters, using all combinations of them would be a lengthy, if not impossible, task. Hence, the computer simulation model contained herein must be limited in scope. The approach, however, should be expandable, with minor modifications, to larger land areas and many vehicle designs with a wide variety of options. For the purposes of this study, it is sufficient to demonstrate the validity of a new approach to mobility evaluation, namely that of digital computer simulation. The vehicles' options are limited, but they are easily expandable to include the full range normally provided by a manufacturer. The varieties of terrain are also limited to a small area. Again, they are easily expandable to larger areas. The entire model is limited only by the computer programming time available and the ability of the experimenter to acquire the required data. Certain restrictions in the size of the model are imposed by the simulation language used. These restrictions are surmountable by utilization of additional programming techniques.

The terrain-vehicle relationship model is primarily restricted in this study to conventional rubber-tired vehicles. Additional assumptions and limitations are covered in detail within the following chapters. The primary terrain restriction in this model is that only soft soil conditions are covered. Coarse soils, snow, and organic soils are not considered within this study. Certain assumptions are further made concerning terrain limitations which will be covered in the following chapters.

The assumptions made for vehicle model construction are that:

1. The vehicle moves at a constant speed while traversing terrain except when it is halted by the terrain.

2. The vehicle has sufficient horsepower to overcome rolling resistance and maintain such constant speed.

3. The driver-vehicle and driver-terrain relationships are, for the purpose of this study, considered to be constant as the vehicle is moving at a constant speed.

4. The vehicle attempts to traverse slopes at the vehicle's most vulnerable angle to tipping.

The assumptions made for terrain model construction are that:

1. Terrain properties follow insofar as possible distributions available from prior research efforts, unless otherwise specified.

2. Soil analogues are correct.

A constant speed is obviously the most unrealistic assumption. However, speed variation, not only with the vehicle-terrain relationships but also those with the driver, rolling resistance, and negotiation of obstacles are all intertwined. The resultant model including all such factors would require a massive research effort. Such research would be a worthwhile expansion of the technique.

CHAPTER II

LITERATURE SEARCH

> Simulation problems are characterized by being mathematically intractable and having resisted solution by analytical methods. The problems usually involve many variables, many parameters, functions which are not well behaved mathematically, and random variables. Thus simulation is a technique of last resort. Yet, much effort is now being devoted to computer simulation because *it is a technique that gives answers* [italics supplied by author] in spite of its difficulties, costs, and time required (16).

The truth of this quotation becomes very evident when one begins to examine the complexities of the terrain-vehicle relationship. In searching the literature of this field, it becomes readily apparent to the investigator that a Pandora's box of disagreement and gaps in knowledge is being opened. Whereas in naval architecture or aeronautical engineering, definite mathematical relationships exist between the vehicle and the medium in which it moves, such is not the case with the automotive engineer.

Although Coulomb (17) first proposed in 1776 a relationship between a wheel and soil based on the sinkage of plates in soil, the relationship is not fully explained today. Bekker (18) proposed in 1956 a relationship that somewhat followed Coulomb's work. This was that:

$$pn = \left(k\phi + \frac{kc}{b}\right) z^n$$

where

pn = nominal ground pressure

$k\phi$ = modulus of soil deformation of frictional soils

kc = modulus of soil deformation on cohesive soils

b = width of loaded area

z = sinkage

n = exponent of deformation

where $k\phi$, kc, and n are determined experimentally. Bekker's equation is reproduced here because it forms the basis for much of the research that has since been performed. The Land Locomotion Laboratory followed Bekker's approach and has attempted refinements of his basic equation. In 1961, Janosi and Hanamoto (19) were dissatisfied with the limitations of the Bekker equation and worked to achieve a more comprehensive relationship. Sela (20) likewise in 1964 considered the Bekker equation to be limited and proposed a further refinement. Reece (21) challenged the equation as being valid for sand but inadequate for cohesive soils. The Bekker equation is still the basis for work done today even though it is constantly criticized. Hoop (22) in 1966 felt that the equation had failings but continued to use it.

The assumptions upon which the Bekker equation is based lead to much of the disagreement. One of these assumptions is a rigid wheel. Obviously, the majority of wheeled vehicles operating today use pneumatic tires. To seek the proper relationship, Haley (23) in 1964 began an initial search into the subject. He was unsuccessful because his apparatus was unsatisfactory and he felt a complete redesign was required. Dimensional analysis was attempted by Freitag (24) of the

Waterways Experiment Station in 1965. Although not completely satisfactory, Freitag felt that it could be employed to explain the pneumatic tire-soil relationship. In 1966, however, while recognizing certain possibilities of dimensional analysis, Liston (25) felt that dimensional analysis was not the proper approach and ruled out further efforts by the Land Locomotion Laboratory in dimensional analysis. Thus, the relationship of the pneumatic tire-soil interaction has not yet been fully explored although it plays a vital role in ground mobility.

The foregoing paragraphs have indicated some of the magnitude of the theoretical research being performed to uncover the true terrain-vehicle relationship. Paralleling this theoretical work is much empirical work. Following World War II, the Mobility Research Branch, Waterways Experiment Station, was given the task of discovering a means whereby ground trafficability could be determined for vehicles in military operations. This task was accomplished and the system was adopted. A detailed description of the system is given in *TB Eng 37*, "Soils Trafficability," dated 1959 (26). Basically two soil values, a cone index and a remolding index, are determined empirically by a simple device. The product of these two indexes is correlated to a Mobility Index which is determined through a formula (obtained by empirical means) which employs vehicle characteristics.

In 1961 Kennedy (27) performed numerous experiments to further refine the existing mobility index equation. The resulting revised mobility index accomplished trafficability prediction with better than 90 per cent accuracy.

Siddell *et al.* (28) of the Canadian Muskeg Research Council proposed a system based on dimensional analysis. He was concerned with muskeg and felt that neither the theoretical approach of the Land Locomotion Laboratory nor the empirical approach of the Waterways Experiment Station could be applied to the specific muskeg type environment.

The Canadian Armament Research and Development Establishment developed a semi-empirical approach based on dimensional analysis which uses the drawbar-pull/weight ratio to determine an index of the vehicle's mobility. (Drawbar-pull is that pulling force exerted by a vehicle after accomplishing its own movement) (29). The obvious fallacy of the system is that maximum force may be exerted at 100 per cent wheel slippage. Dickson (30) proposed a revision which included the velocity of the vehicle. Tests conducted by Liston (31) in 1966 indicated that drawbar-pull measures the ability of vehicles to operate in weak soils but there were many other factors which dominated the drawbar-pull/weight ratio.

Along with their work to measure soil trafficability, the Waterways Experiment Station strived to achieve a system whereby terrain could be quantified. The results of the initial efforts of the Waterways Experiment Station were presented to the 1st International Conference on the Mechanics of Soil-Vehicle Systems in 1961. The paper presented was prepared by Van Lopik and Compton (32) and represented the direction of the Waterways Experiment Station's efforts. The method was refined in tests conducted both in the United States and overseas. The method evolved through the formulation of an analytical model for predicting the cross country performance of ground-contact military vehicles (33).

Considerable experimentation was performed by the Waterways Experiment Station with actual vehicles in the early sixties. A multitude of reports came out relating the ability of various vehicles to negotiate different trafficability conditions. Typical of these reports was "Trafficability Tests with a 5 Ton GOER (XM520) on Fine and Coarse Grain Soils" written by Rush (34) in 1962.

The Waterways Experiment Station applied their quantitative approach to selected areas in Thailand in 1965 and quantitatively mapped areas of the country. They recognized that the magnitude of the area required that much work be done through interpretation of aerial photographs. Through proper sampling and ground control, this interpretation was accomplished and a final report prepared and published (35). This application of the quantitative method has continued and the Waterways Experiment Station published in 1968 the results of a study in Puerto Rico (36).

One of the major trouble areas encountered by the Waterways Experiment Station in developing their quantitative approach was the necessity for a comprehensive soil classification system. The Waterways Experiment Station desired to use the United States Department of Agriculture Soil Classification due to the extensive areas of the world already mapped under the system. Two major stumbling blocks were encountered in applying the system used by the Department of Agriculture. First, there was the problem of the many different types of soils indexed qualitatively under the system and second, certain countries of the world would not be particularly interested in permitting representatives from the United States to prowl around the countryside gathering soil trafficability parameters.

To alleviate the problem of the numerous soil types encountered under the United States Department of Agriculture Soil Classification System, the Waterways Experiment Station conducted tests to determine the level at which further subclassification would be unnecessary. In 1966, Bassett *et al.* (37) published the results of their work with soils encountered in Louisiana and Arkansas. They concluded that prediction at the soil series level was adequate for trafficability analysis of the four loess soil series studied. Any additional accuracy obtained through further subclassification was lost through the inaccuracies of the trafficability prediction system. Basset *et al.* (38) recommended that further experiments be conducted on other similarly related soil series to determine the feasibility of grouping for trafficability purposes. Carlson *et al.* (39) issued another report in 1967 relating the variation of physical properties of loess soils.

The second problem faced by the Waterways Experiment Station was approached through the use of soil analogues. In this research, considerable assistance was rendered to the Waterways Experiment Station by the Land Locomotion Laboratory. Lassaline and Harrison (40) concluded that soil analogues were reasonable and practical for predicting soil strength parameters. A continuation of the study of soil analogues was conducted by Harrison and Chang (41) in the following year. Again it was concluded that prediction of soil strength parameters at the Series Level would be sufficient. Numerous experiments were conducted throughout the Northeast and Northcentral United States to support their findings.

It must be noted here that the Land Locomotion Laboratory system of describing soil strength is not the same as the system used by the Waterways Experiment Station. However, in 1964 the Waterways Experiment Station conducted a series of experiments to determine the strength-moisture-density relations of fine-grained soils and concluded that the system used by the Waterways Experiment Station can be correlated to the Land Locomotion Laboratory system (42).

Another effort of the Waterways Experiment Station has been to determine the statistical nature of terrain. Siddell *et al.* (43) of the Muskeg Research Council mentions the large number of significant terrain variables of a stochastic nature as being a major stumbling block to the development of a mathematical model. Although speaking specifically of muskeg, Siddell goes on to state that a statistical approach is essential in any treatment of terrain. Under the auspices of the Waterways Experiment Station, the Department of Civil Engineering, The University of Tennessee (44), conducted an environmental survey of Ranger training areas. These Ranger training areas are located at Fort Benning, Georgia; Dahlonega, Georgia; and Eglin Air Force Base, Florida. Geology, hydrology, macrogeometry, and vegetation were considered and examined. The study is particularly informative in its treatment of slope variations and vegetation. Bassett *et al.* (45) conducted a statistical treatment of variations in trafficability indexes in the four loess soils studied. The majority of statistical work, however, has been done in determining ground roughness.

Perhaps because the soil-vehicle relationship is not fully understood, there has been much work done considering the effect of vehicle vibration caused by ground roughness. Since vehicle vibrations do play a large role in the human factor, the area receives much attention. Stone and Dugundji (46) propose ground roughness to be a Fourier Series. While not mentioning the mathematical properties of ground roughness, Liston (47) lists the vibration caused by it as a significant factor overriding the drawbar-pull/weight ratio as a determination of vehicle mobility. The Waterways Experiment Station published an instruction report on the collection of microgeometry (48). Stollmack (49) in his report on the tank weapon system devoted one full sub-report to the nature of ground roughness and means of generating it. The power spectral density is discussed fully by Bogdanoff *et al.* (50) and the statistical data upon which their work is based is presented.

Vehicle computer simulation techniques are relatively new. While terrain profiles have been simulated for some time in military war gaming, it was the response of military tactical units to terrain that interested the investigator rather than specific vehicles. Both Meyer (51) and Davis (52) discuss in detail the various military war games that consider terrain; however, in the field of vehicle computer simulation, little has been done. Perloff (53) as part of his role in determining tank mobility, wrote a special purpose program to be used in determining tank mobility. Perloff's model was based on Bekker's 1960 approach with refinements. The model is concerned only with soil sinkage as it relates to the ability of the tank to overcome soil resistance. Slope is thus seen as influencing the ability of the tank to overcome soil resistance which has been increased through the shifting of forces. The ability of the track to maintain its grip without slippage is also considered.

Perloff's model was a submodel to the entire tank weapon system (54). While interesting, the other portions of the model dealt with military applications and would be inappropriate here. Perloff unfortunately had no means to validate his model. While he felt that his results looked reasonable, there was not any experimental verification of its predictive ability.

Another computer simulation model was developed by McKenzie *et al.* (55) of General Motors Corporation. They developed two models for "Computerized Evaluation of Driver-Vehicle-Terrain Systems." An analog computer model was developed for a 4 × 4 rigid framed, wheeled vehicle and a digital computer model was developed for a single-frame tracked vehicle. Both models were based on work by Bekker who was at General Motors Corporation at this time. These models considered terrain roughness, soil traction slip characteristics, and vehicle power and the interaction thereof. The effect of terrain roughness was concerned with the vibratory accelerations to which the driver of a vehicle is subjected. Sinkage and slippage were considered as forces acting in opposition to vehicle power. The simulation did not evaluate the vehicle against terrain but rather the reaction of the driver to terrain and the resultant effect upon the vehicle.

The foregoing paragraphs have indicated some of the diversity of effort that is being expended in the field of determining ground mobility, but when this effort is considered relative to other fields of endeavor it is very small. At the Advanced Research Projects Agency workshop on improvement of off-the-road mobility, one of the major complaints heard was that, while the army was spending approximately equal amounts on ground vehicles and aircraft, the research funds for the latter were approximately 100 times as great as for the former (56).

Today, while many are working on the problem, there is still no definite way of describing ground mobility. While Bekker's technique appears to afford a theoretical approach, it is subject to many errors. The empirical approach is not satisfying from an aesthetic viewpoint but it does appear to give results.

The lack of extensive previous work in vehicle mobility simulation precludes a definite approach to be taken. No significantly useful means of evaluation have been discussed by earlier workers in this area. While the authors felt their work to be reasonable, they could not verify it.

Mobility simulation is a highly subjective field at this time. It offers to the participating individual full opportunity to make a significant contribution to vehicular design practices. The random variables which have created much of the confusion are tailored for computer simulation techniques.

CHAPTER III

PROCEDURE

Approach to the Problem

To accomplish the objective of this study, the terrain-vehicle system must be quantitatively described and modeled. Specifically, a typical pulpwood harvesting vehicle must be evaluated for its ability to traverse the terrain which comprises the pulpwood resource areas in which it may be expected to operate. A computer simulation model is required to simulate the movement of a vehicle across a specified piece of terrain. During this movement, the characteristics of the vehicle must be quantitatively compared against the characteristics of the terrain. The simulation of the terrain over which the vehicle passes must demonstrate the stochastic nature of that terrain. The method of evaluation is simply the ratio of successful passes over total attempts. If a sufficiently large number of trials are conducted, this ratio will reflect the probability that a pulpwood harvesting vehicle will successfully harvest a given acreage of land that has specified variables.

The quantitative description of the terrain-vehicle system uses the Waterways Experiment Station's method of quantifying terrain and determining vehicle soft soil mobility. Shamburger (57) provides a detailed description of the terrain classification system. Under the Waterways Experiment Station system, there are four factor families within terrain. These factor families are: surface composition (which is soil trafficability), surface geometry, vegetation, and hydrology. The trafficability of surface composition is computed by a rating cone index. This rating cone index correlates to a vehicle mobility index. The result is a go-no go relationship. Surface geometry is the slope and microgeometry of the terrain. This surface geometry correlates to the center of gravity of the vehicle and its ground clearance. Vegetation correlates to the force available to the vehicle to overcome the resistance of the vegetation and the ability of the vehicle to negotiate among the larger vegetation such as trees. Hydrology correlates to the fording capability of the vehicle as well as its ability to negotiate stream banks and stream bottoms. The Waterways Experiment Station system is thus quantifiable and adaptable to computer simulation.

Having defined the quantitative relationships of the terrain-vehicle system, it was then necessary to describe the system for translation into a computer simulation language. The system was defined as a vehicle moving across terrain in the manner described in the first paragraph of this chapter. To portray this passage, the vehicle was evaluated against the terrain once for each movement of one vehicle length. The total distance to be traversed was set at 1,000 yards. As the vehicle proceeded over the terrain, it might be halted through inability to negotiate the soil, it might tip over, the power could be lacking to overcome vegetation, or terrain obstacles would be insurmountable. Vehicle speed was not considered and the model was strictly "go" or "no go" on each evaluation.

Following the description and formulation of the model, a computer simulation model was constructed. General Purpose Systems Simulator II was chosen as the computer simulation language. The computer model was validated by using available data to check each factor family. The program was designed so that the values of variables were printed out as well as the values contained within the transactions themselves. These printouts permitted the full analysis of the program.

The completed simulation model was used to predict the probability of a typical pulpwood harvesting vehicle, as described by Freitag (58), negotiating typical pulpwood resource areas as might be encountered in the state of Georgia. Several different sites were used to test at what point vehicle failure occurred. To increase the accuracy of the simulation, replications were performed at each level using different random number seeds.

All variables represent actual vehicle characteristics and terrain characteristics. Where actual data were available, it was used in the system. When data were not available, every attempt was made to assume values which appeared to be reasonable and consistent with other prior research.

Simulation Language Employed

This model could have been constructed in any general purpose language such as ALGOL or FORTRAN. Likewise, any one of several special purpose languages could have been used. The advantages of using GPSS II are several. The primary problem with selling the results of simulation is convincing the individual concerned that the results are valid. With GPSS II, the flow chart is understandable by most people with a moderate education. In this particular simulation model, the program would generate a transaction (vehicle) which would pass through a gate and enter the test track. The program evaluated the vehicle characteristics against all four factor families on each loop. A loop was one vehicle wheel-base length. The program performed loops until the 1,000 yards of the terrain were completed or the vehicle was halted. A record was made of where the vehicle stopped and why it was stopped. The gate then opened and another transaction was permitted to enter the test track. This continued until the appropriate number of vehicles had attempted the test track. GPSS II lends itself particularly well to a situation such as this where a queing analogy can be drawn and a gathering of statistics is required.

General Language Description

To assist the reader, a brief description of some of the GPSS II language characteristics will be given here. By no means complete, the listing covers only those principle language characteristics employed in this simulation model. A complete description of the language may be found in the *UNIVAC 1108 General Purpose Systems Simulator II Reference Manual* (59).

The GENERATE block performs as the name implies. The block generates a transaction which enters the system. Once the transaction has entered the system, a new transaction is created.

The GATE block acts as a gate to prevent transactions from entering the system until desired.

The SPLIT block creates a duplication of the transaction to include duplicating any characteristics that may be assigned as the transaction's parameters.

The ASSIGN block assigns specified values to the transaction's parameters.

The LOGIC block sets to 1 or resets to 0 a specified LOGIC switch that accompanies the transaction through the system. LOGIC switches survive the reassembly of duplicate transactions, whereas the duplicate's parameters do not.

The ADVANCE block permits the selection of a number of exits. In this model, if the COMPARE block refuses entry to a transaction then the transaction looks to the preceding ADVANCE block for another exit to take.

The COMPARE block refuses entry to a transaction unless the relationship specified is satisfied.

The SEIZE block specifies the entrance to a facility. No other transaction can occupy or use the facility until the using transaction passes through the RELEASE block which releases the facility for use by another transaction.

The SAVEX block permits the storing of values within the model. Parameter or variable values may be stored at any point in the program to be printed out as directed by a corresponding PRINT block.

The LOOP block permits any portion of the program preceding the LOOP block to be repeated a specified number of times. The transaction encounters the LOOP block and, if it has the required number of repetitions, may proceed to the next block in the program.

The ASSEMBLE block reassembles the transactions that had been duplicated in the SPLIT. In the process, the ASSEMBLE block destroys the duplicate transaction and any parameter values the duplicate may have had.

The TERMINATE block performs as the name implies. It terminates the life of the transactions.

These listed blocks comprise only a small portion of the total capability of GPSS II. However, with them, it is possible to construct a highly realistic model that portrays the terrain-vehicle relationship.

CHAPTER IV

DESCRIPTION OF THE MODEL

General Description

While detailed knowledge of GPSS II is not required to understand the computer simulation model presented here, the reader is presumed to have familiarity with the language. This familiarity should be sufficient to understand the modified flow charts contained within this chapter. For the programmer having complete knowledge of GPSS II, the complete computer program is listed in Appendix B. Most readers desiring only familiarity with the approach should find this chapter sufficient.

As shown in Figure 1, the model consists basically of three major sections: a vehicle characteristics assignment section, a vehicle evaluation section, and a data collection section. Within each section are several sub-sections. By its nature, the data collection section has sub-sections spread throughout the vehicle evaluation section which permit the collection of the necessary data. The vehicle characteristic assignment section and the vehicle evaluation section are subject to changes between experiments.

The vehicle characteristic section generates the vehicle and then assigns the characteristics to the vehicle as parameters where necessary. The mobility index of the vehicle must be computed as shown in Figure 2. The mobility index is then correlated to a vehicle cone

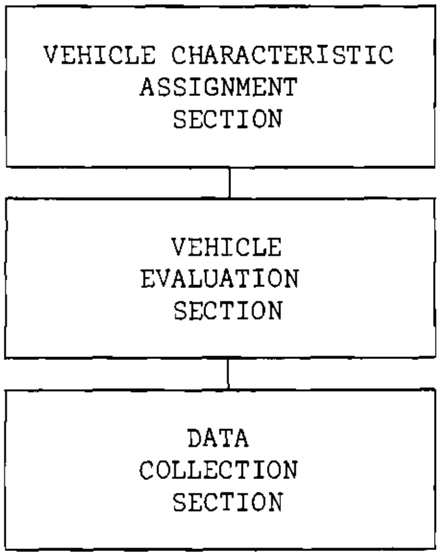

Figure 1. General Model Outline

index (Figure 3) by the vehicle characteristic section. The section also holds the vehicle until the vehicle evaluation section is clear of the old vehicle. The new vehicle is then permitted to enter the vehicle evaluation section.

The vehicle evaluation section performs the function of evaluating the vehicle characteristics against the terrain characteristics once for every vehicle wheelbase length. It performs this evaluation repetitiously until the vehicle traverses the test course length of 1,000 yards. If for any reason, the vehicle is halted by a terrain characteristic and can progress no further, then the vehicle evaluation section releases the vehicle and permits the vehicle to enter the data collection section. The vehicle evaluation section is then clear to accept a new vehicle.

The data collection section has sub-sections spread throughout the programs. The section records the number of vehicles that are

$$MI = \left\{ \frac{\text{Contact Pressure Factor} \times \text{Weight Factor}}{\text{Tire Factor}} + \text{Wheel Load Factor} - \text{Clearance Factor} \right\} \times \text{Engine Factor} \times \text{Transmission Factor}$$

$$\text{Contact Pressure Factor} = \frac{\text{Gross Weight, Lbs.}}{\text{Nom. Tire Width, In.} \times \dfrac{\text{Outside Diameter Tire, In.}}{2} \times \text{No. of Tires}}$$

Weight Factor:

Weight Range (Lb)*	Weight Factor Equation
< 2,000	Y = 0.553X
2,000 to 13,500	Y = 0.033X + 1.050
13,501 to 20,000	Y = 0.142X - 0.420
> 20,000	Y = 0.278X - 3.115

Tire Factor: $\dfrac{10 + \text{Tire Width, In.}}{100}$

Wheel Load Factor: $\dfrac{\text{Gross Weight (Kips)}}{\text{No. of Wheels}}$

Clearance Factor: $\dfrac{\text{Clearance, In.}}{10}$

Engine Factor: > 10 hp/ton = 1.00
< 10 hp/ton = 1.05

Transmission Factor: Hydraulic = 1.00
Mechanical = 1.05

Figure 2. Mobility Index Computation [Kennedy *et al.*, *Revised Mobility Index*]

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* $\left(\dfrac{\text{Gross Weight (Lbs.)}}{\text{No. of Axles}}\right)$

Y = Weight Factor

$X = \dfrac{\text{Gross Weight (Kips)}}{\text{No. of Axles}}$

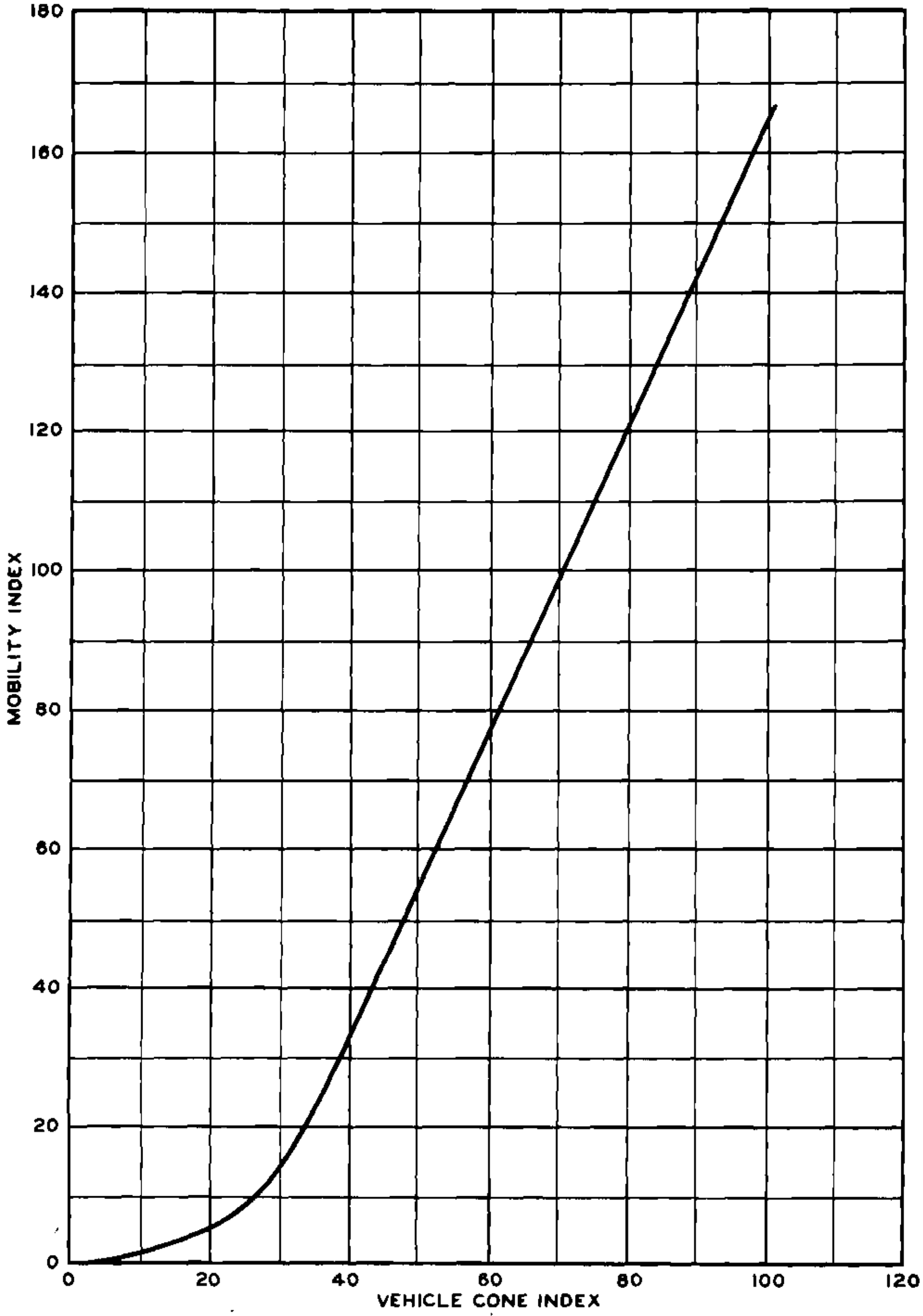


Figure 3. Mobility Index Versus Vehicle Cone Index [Kennedy *et al.*, *Revised Mobility Index*]

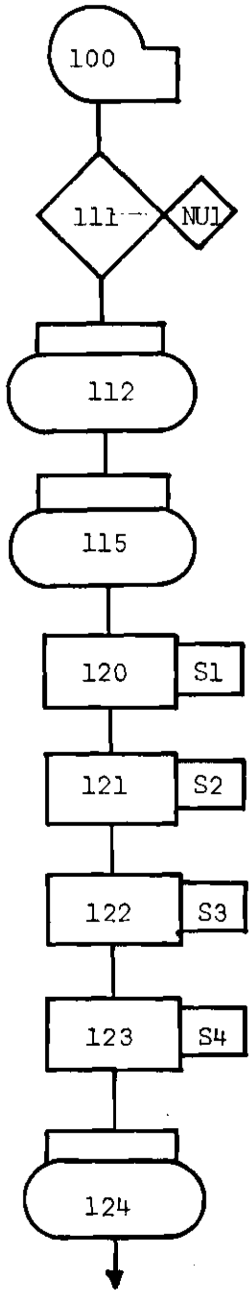


Figure 4. Vehicle Characteristic Assignment
Section Flow Chart

successful in negotiating the vehicle evaluation section in all experiments. If the vehicle does not successfully negotiate the vehicle evaluation section, then the data collection section records which terrain characteristic halted the vehicle and at what point in distance the vehicle was stopped. After the data are collected, the data collection section releases the vehicle to a termination block where the vehicle's existence is terminated.

FUNCTION and VARIABLE statements are used throughout the specific sections. These statements are explained in the order in which they occur in the program. A recapitulation is included in the program listing.

Specific Sections

Vehicle Characteristic Assignment Section

In the vehicle characteristic assignment section, the necessary task of describing the vehicle and rendering its characteristics into usable form is performed. Because the Waterways Experiment Station's method of computing soft soil mobility is used, the mobility index of the vehicle must be computed. This computation is then correlated to a vehicle cone index within the vehicle characteristic assignment section. Another task that occurs within this section is the setting of LOGIC switches which permit necessary data to be retained later in the program. These steps plus the generation of vehicles and their retention prior to entering the test track are all performed within the vehicle characteristic assignment section.

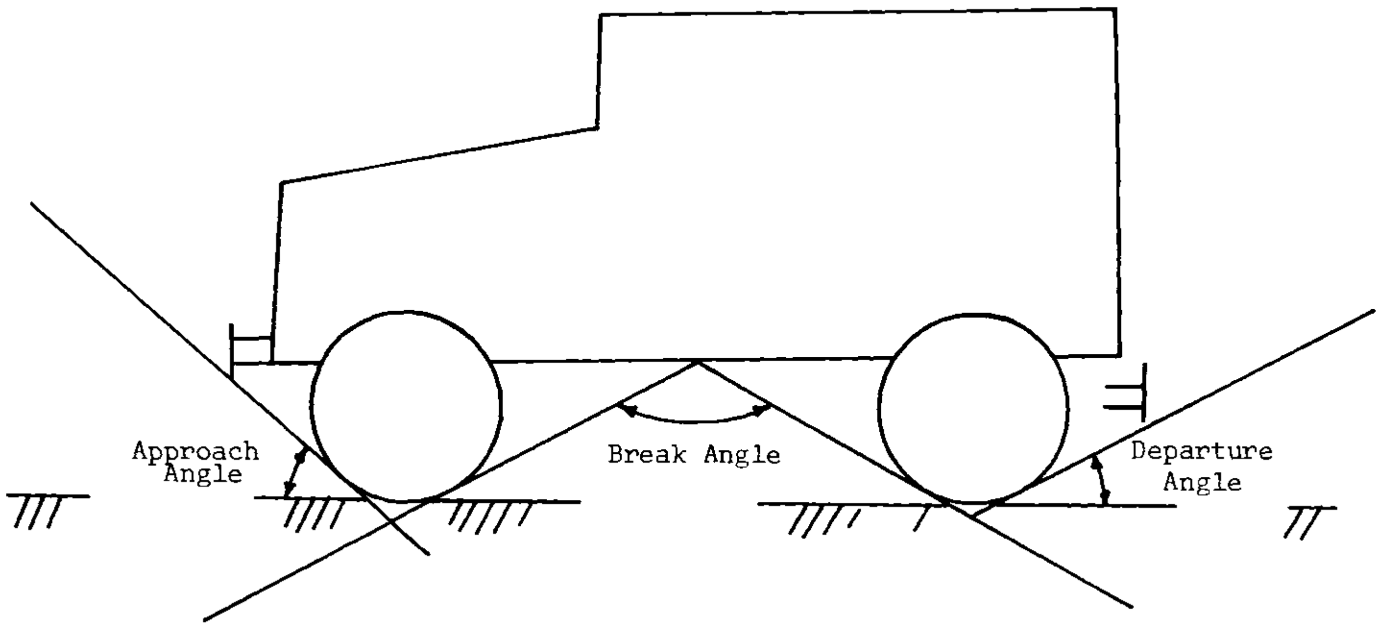


Figure 5. Approach, Break, and Departure Angles

The initial VARIABLE statements which define the vehicle characteristics for the simulation model are listed in Figure 6. All of these statements are constants and their values are prefixed by a K to designate them as such. The manner in which these variables are obtained is self-evident except for approach angle, departure angle, and break angle. A diagram is shown as Figure 5 which demonstrates the angles as well as the various other vehicle dimensions.

V1	Wheelbase
V2	Horsepower
V3	Outside Tire Diameter
V4	Overall Vehicle Length
V5	Vehicle Ground Clearance
V6	Height to Center of Gravity
V7	Vehicle Track
V8	Approach Angle
V9	Departure Angle
V10	Break Angle
V11	Value for Vehicle Suspension
V12	Value for Vehicle Flotation
V13	Turning Radius
V14	Tire Width
V15	Vehicle Weight
V16	Number of Tires
V22	Number of Axles
V28	Transmission Factor
V30	V30 Mobility Index
V41	Maximum Drawbar Pull

Figure 6. List of Variables Assigning Values for Vehicle Characteristics

Block 100 is a GENERATE block which generates the vehicle as required. After the vehicle is generated, it waits until GATE, block 111, permits the vehicle to pass through on the basis of whether or not the test track, facility 1 is in use. If facility 1 is not in use, NU1, then the vehicle is allowed to proceed.

ASSIGN block 115 calls for VARIABLE 31, the computed value of the total track length, 36,000 inches, divided by the vehicle's wheelbase, to be assigned to parameter 3. This value will later tell the program how many times each vehicle is to be evaluated against test track conditions.

Blocks 120, 121, 122, and 123 are LOGIC blocks which set logic switches 1, 2, 3 and 4, respectively, to 1. Later in the program, if the vehicle is stopped by any terrain obstacle, these logic switches are reset to 0 and the vehicle immediately exits the test track recording which terrain obstacle stopped it. The LOGIC switches set here make the operation possible.

Block 124 is an ASSIGN block which assigns a constant of 1 to parameter 8 of the vehicle. Parameter 8 is the counter for the number of times the vehicle has been evaluated against the various terrain factor families.

The vehicles characteristics have now been defined and assigned as parameters where necessary. The vehicle now enters the next section of the program, the vehicle evaluation section.

Vehicle Evaluation Section

General. The vehicle evaluation section has four major sub-sections. These sub-sections are Factor Family 1, Factor Family 2, Factor Family 3, and Factor Family 4. As seen in Figure 7, the section seizes the vehicle, splits the vehicle into an original and three duplicates, evaluates the vehicle, and loops it the necessary number of times. Since the factor families have sub-sections within themselves,

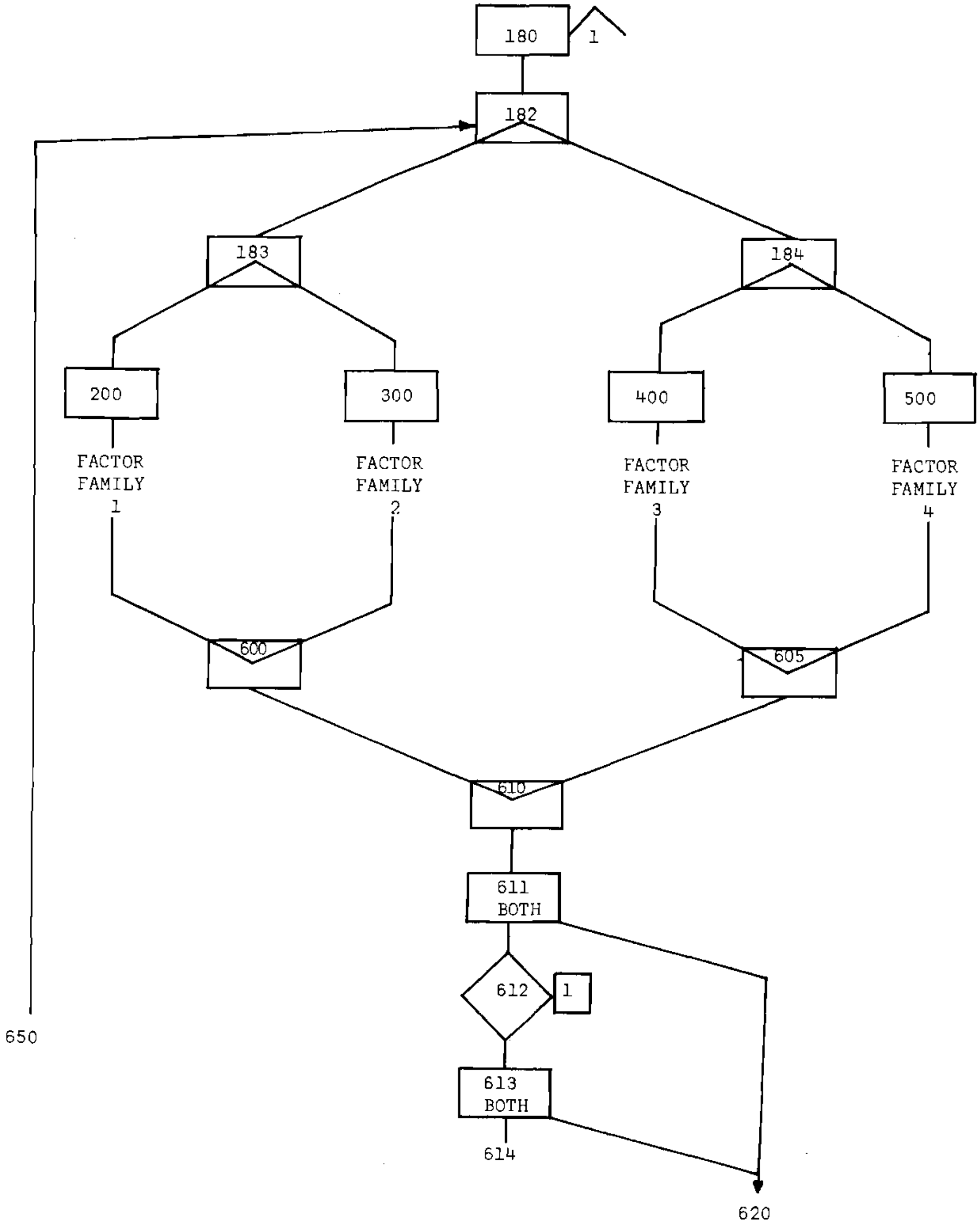


Figure 7. General Flow Chart for Vehicle Evaluation Section

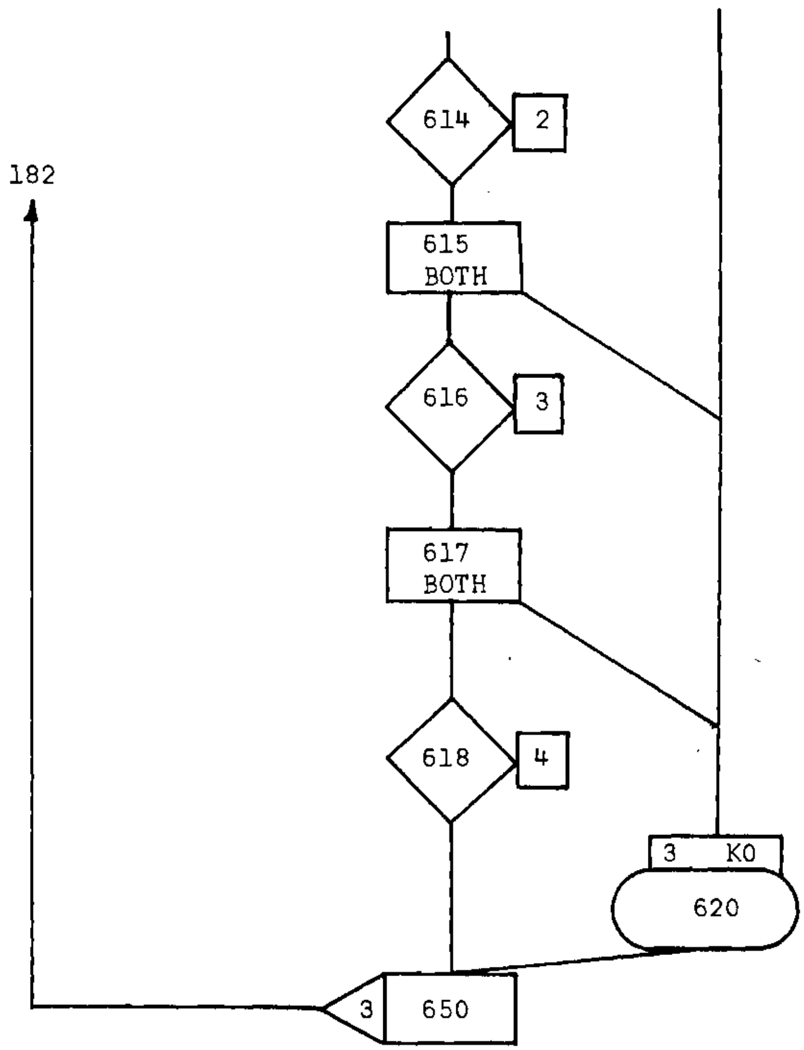


Figure 7. General Flow Chart for Vehicle Evaluation Section
(Continued)

only the general concept of the entire section will be covered here and each factor family will be explained in detail within a sub-section under this heading.

The initial blocks in this sector cause the section to be seized by the vehicle entering it. This is accomplished by SEIZE block 180. SPLIT blocks 182, 183, and 184 then create three duplicates of the original for a total of four vehicles, one of each of which will go through each evaluation sub-section. Blocks 600, 605, and 610 are REASSEMBLE blocks which cause the program to revert to one vehicle. The vehicle then passes through a series of GATE blocks--612, 614, 616, and 618 which check to see if any logic switches have been reset. If a logic switch has been reset, then ADVANCE blocks 611, 613, 615, and 167 using the BOTH selection made will send the vehicle to ASSIGN block 620 where a value of 0 is assigned to parameter 3. Since LOOP block 650 looks to parameter 3 for the number of loops remaining to be performed, when a zero is encountered the vehicle exits the vehicle evaluation section to enter the data collection section.

The vehicle is considered not to be immobilized until three successive vehicle lengths of soil fail to have the necessary supportive rating lane index. This indicates the effect of vehicle momentum which would enable the vehicle to cross short soft spots.

Factor Family 1 Sub-section

After seizure by block 200, the vehicle goes through a series of SAVEX blocks, 205, 206, 207, which store the values of the soil over which the vehicle is passing. A moving average is maintained of the three most current soil index values. The current value is obtained from FUNCTION 2 which was shown as Figure 3. A random number is generated which permits the readout of the soil cone index for each loop of the program. SAVEX block 208 and PRINT block 209 record and print the averaged soil index value. If the average of the three soil readings is greater than the vehicle cone index rating, FUNCTION 1 which correlates the mobility index to a vehicle cone index rating, COMPARE block 220 passes the vehicle through ASSIGN block 221 and SAVEX block 222 which counts and saves the number of times the vehicle has been evaluated for soft soil mobility. If COMPARE block 221 refuses passage to the vehicle then the vehicle goes to LOGIC block 225 where logic switch 1 is reset to 0. Release block 230 terminates Factor Family 1 evaluation.

Factor Family 2 Sub-Section

The slope and microgeometry evaluation sub-section evaluates the vehicle on its stability. To accomplish this requires that the ground slope, which varies within certain limits, be evaluated and the effect of the microgeometry be evaluated. Since both ground slope and microgeometry are random factors, their values are determined through FUNCTION 4 and FUNCTION 5, respectively. Figure 12 describes the general nature of these two functions. The vehicle is evaluated for its stability when being acted upon by these factors. Figure 10 illustrates the relationships involved. The determination of stability is made by the location of the center of gravity for the vehicle. If the center of gravity lies outside of the vehicle track, then the vehicle is unstable or in Figure 12, a is greater than b.

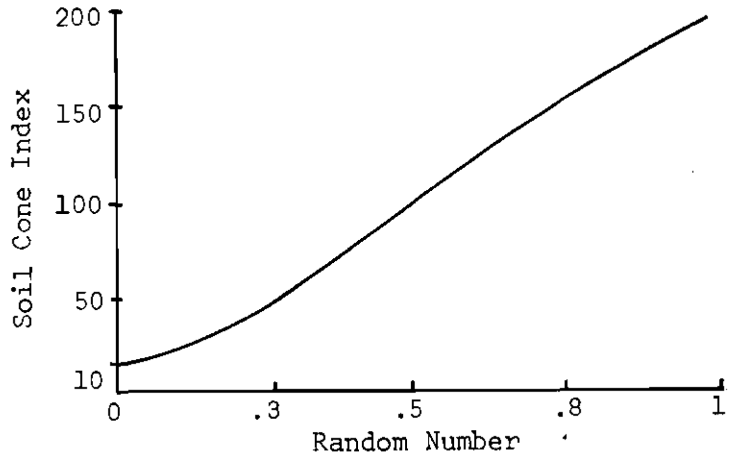


Figure 8. General Nature of Determining Function Values [Illustrative Data]

This series of events is accomplished through VARIABLE statements and FUNCTION statements while all functions are listed in Chapter V as part of the experiments conducted, only the function's purpose will be described here. FUNCTION 6 calls on VARIABLE 37 for the angle of slope and gives the sine of that angle. FUNCTION 7 also calls on VARIABLE 37 and provides the cosine of that angle. FUNCTION 8 calls upon parameter 4 to go from sin W to cos W directly. Parameter 4 has stored the value of VARIABLE 46 which is sin W.

SEIZE block 300 causes the slope and microgeometry sub-section to be seized by the vehicle coming through the facility. ASSIGN block 301 places the value of VARIABLE 46 in parameter 4 of the transaction. The value of VARIABLE 47, the distance that the center of gravity is to the outside, is compared with VARIABLE 49, the distance provided by the wheel track for stability, by COMPARE block 310. If the vehicle is

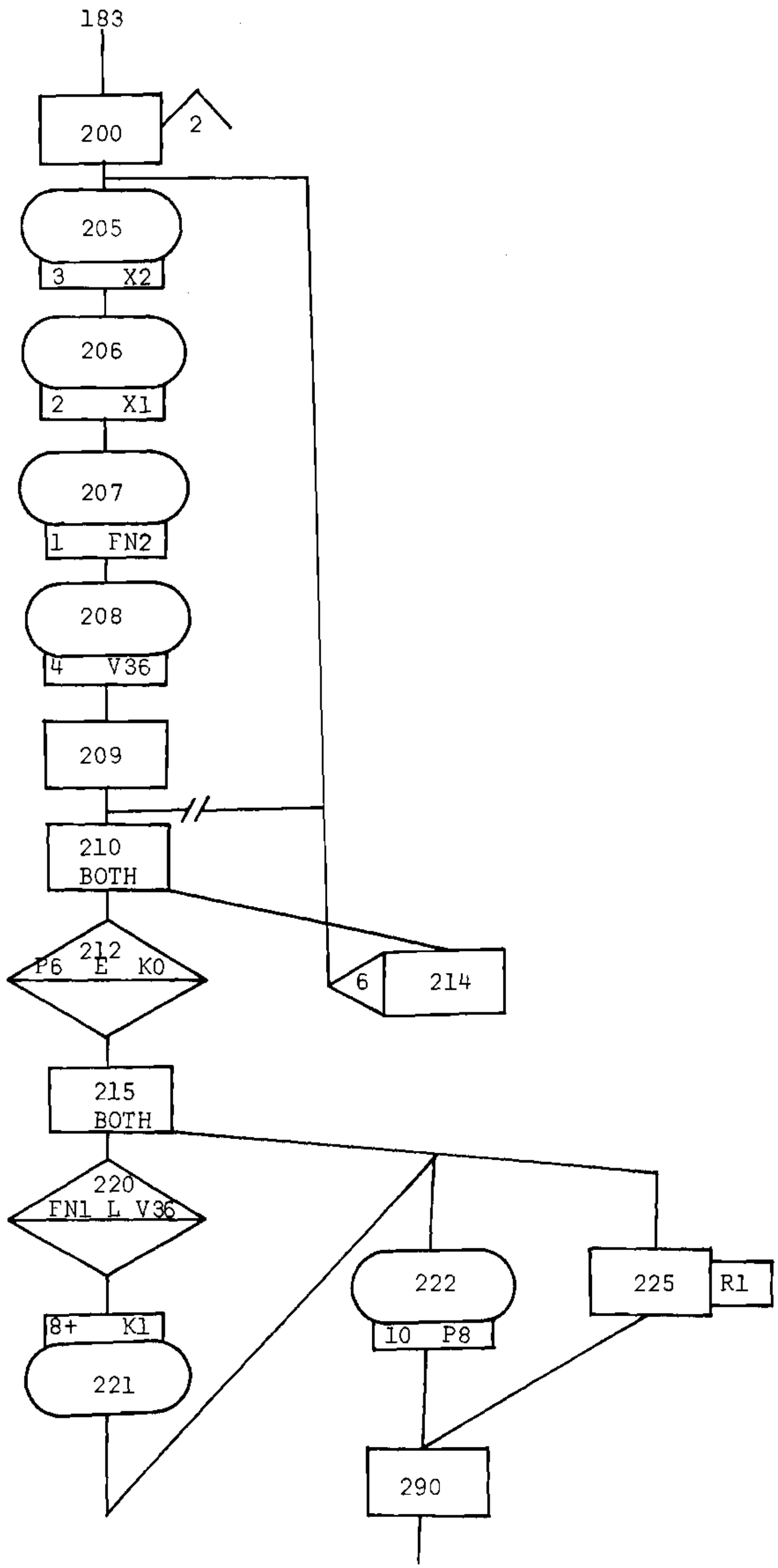


Figure 9. Factor Family 1 Evaluation Sub-Section Flow Chart

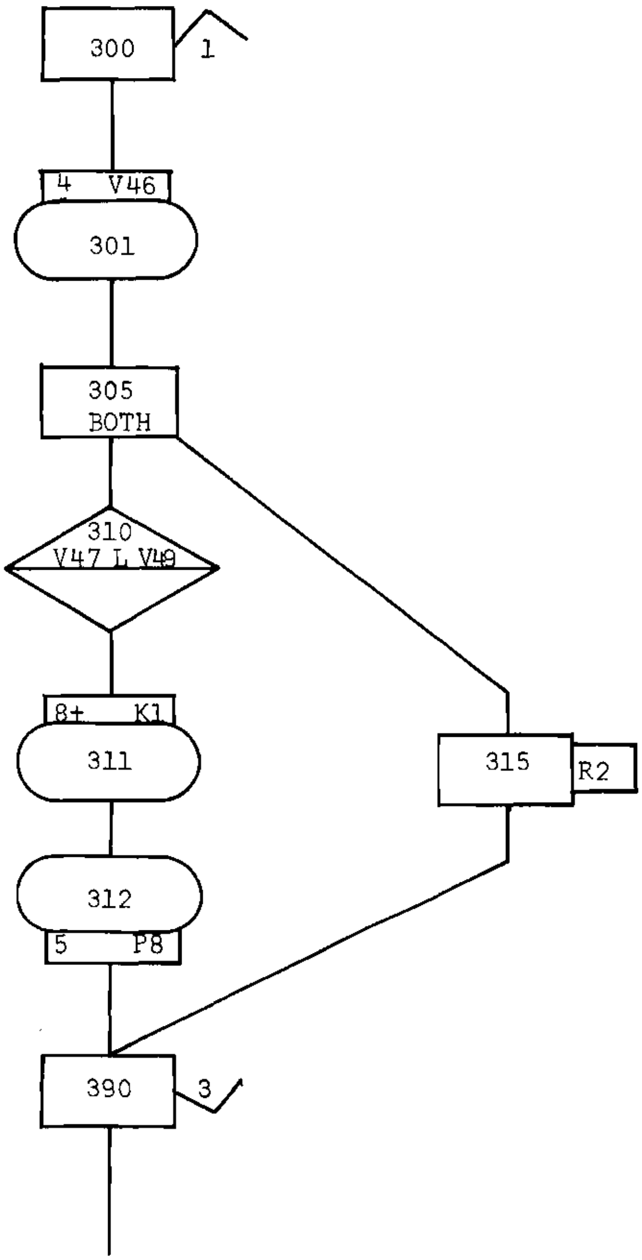


Figure 10. Factor Family 2 Evaluation Sub-Section Flow Chart

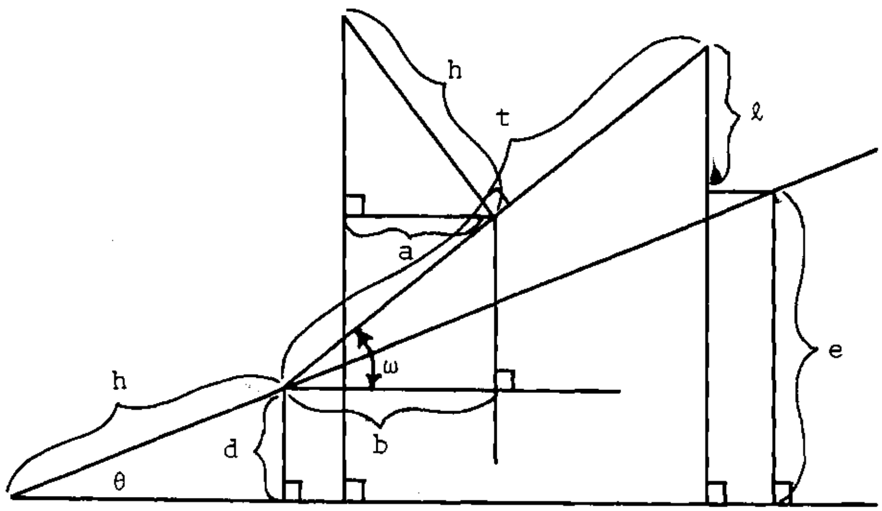
V37	Ground Slope in Degrees
V46	Sin W
V47	h Sin W
V49	1/2 to Cos W

Figure 11. List of Variables Used to Determine if the Vehicle is Stable

stable, then the vehicle proceeds to ASSIGN block 311 and SAVEX block 312 which counts and stores, respectively, the number of successful completions by the vehicle. If the COMPARE refuses passage by the vehicle, ADVANCE block 305 causes the vehicle to enter LOGIC block 315 where logic switch 2 is reset to 0. The vehicle then exits through RELEASE block 390 to enter the data collection section.

Factor Family 3 Sub-Section

This sub-section evaluates the ability of the vehicle to overcome the vegetation of an area. The resistance of the vegetation is measured against the drawbar pull of the vehicle. If the vehicle lacks the power to overcome the resistance of the vegetation, then the driver is assumed to attempt twice more in an effort to maneuver around the vegetation. The resistance of the vegetation is given by the sum of FUNCTION 9, FUNCTION 10, and FUNCTION 11, Figure 10, which represent light, medium, and heavy vegetation, respectively. The resistance represented by the three functions is for a square 10 yards on a side. The vehicle's area is represented by the vehicle track times its length. This vehicle area figured as a percentage of the 30-foot square times the area resistance gives the resistance facing the vehicle.



θ = Ground Slope = V37
ℓ = Microgeometry = FN5
t = Vehicle Track = V7
h = Height to Center of Gravity = V6
ω = Combined Slope and Microgeometry
c = (h + t)sin θ
d = h sin θ

$$\omega = \text{arc sin}\ \frac{\text{hsin}\ \theta\ +\ \text{tsin}\ \theta\ -\ \text{hsin}\ \theta}{t + h} = \text{arc sin}\ \frac{\text{tsin}\ \theta}{t + h}$$

a = h sin W
b = 1/st cos W

Figure 12. Vehicle-Slope and Microgeometry Relationship

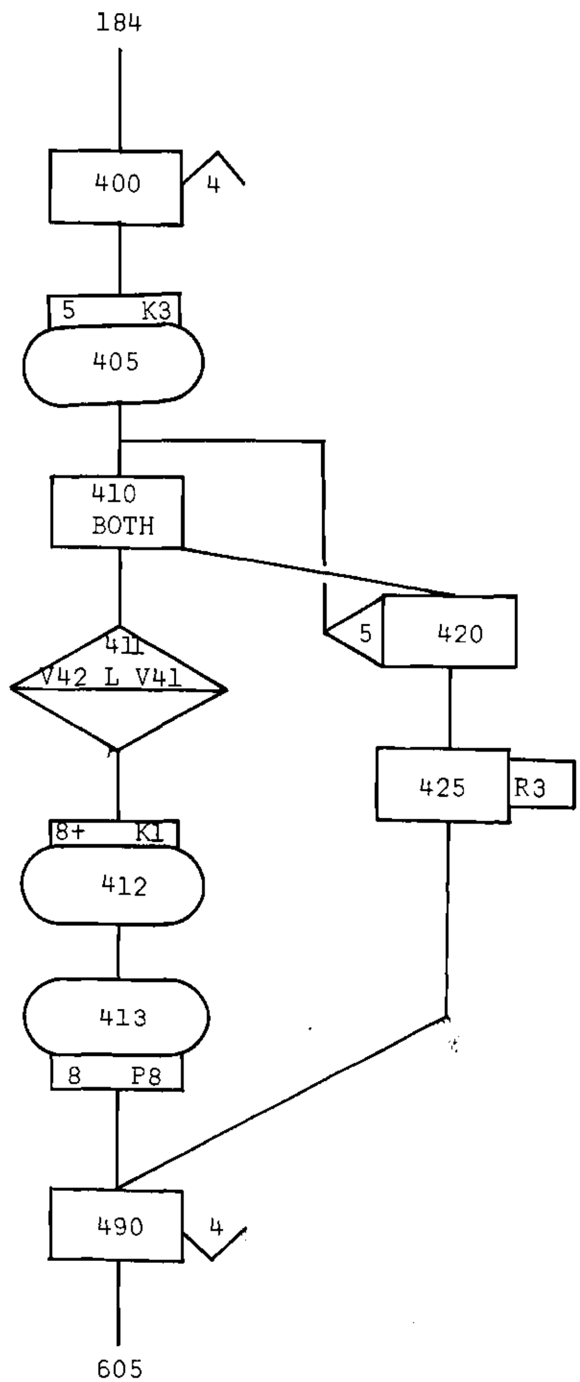


Figure 13. Factor Family 3 Evaluation Sub-Section Flow Chart

FUNCTION 9

FUNCTION 10

FUNCTION 11

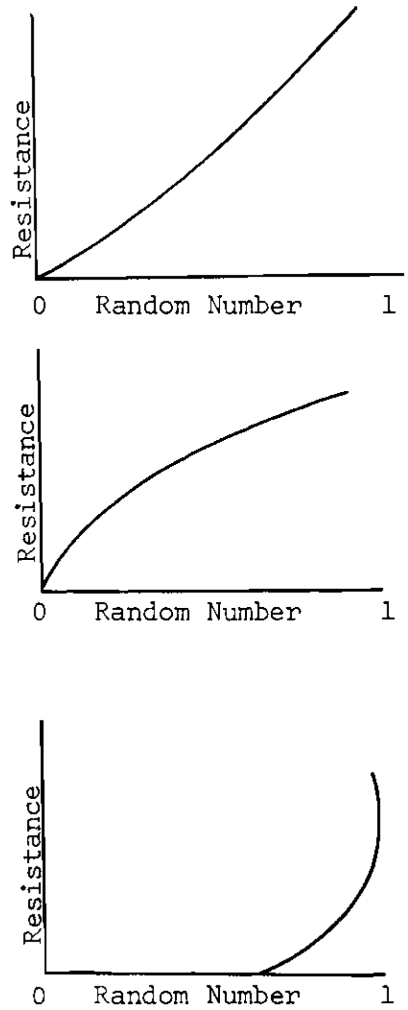


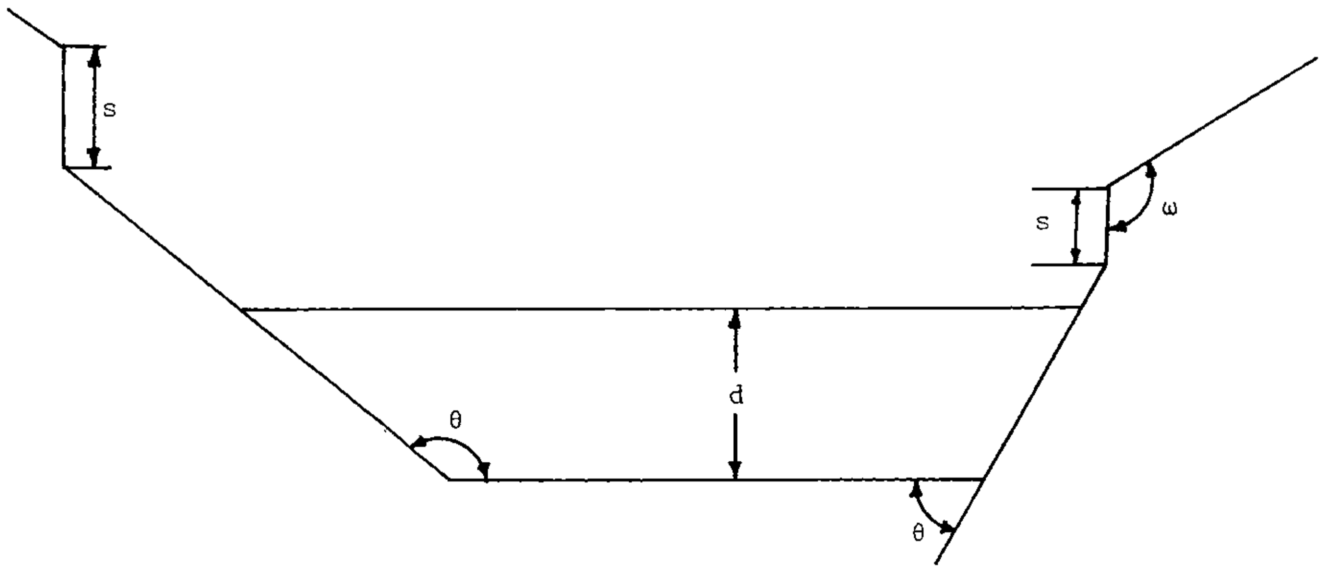
Figure 14. General Nature of Functions Used to Determine Vegetation Resistance [Illustrative Data]

The above sequence of events begins with SEIZE block 400 which seizes the facility for the vehicle. VARIABLES 40, 41, 42, and 50 determine the resistance of the vegetation which is measured against vehicle drawbar pull in COMPARE block 411. ASSIGN block 405 has already assigned a constant of 3 to parameter 5; if the COMPARE block refuses entry LOOP block 420 looks to parameter 5 and recycles the vehicle for another try until a 0 exists in parameter 5. ASSIGN block 412 and SAVEX block 413 store and print, respectively, the number of times the vehicle has passed through successfully, the Factor Family 3 Evaluation Sub-Section. If the vehicle is not successful after 3 attempts to enter the COMPARE block, then the vehicle moves to LOGIC block 425 where logic switch 3 is reset to 0. The vehicle then exists through RELEASE block 430 to move to the data collection section.

Factor Family 4 Evaluation Sub-Section

This sub-section evaluates the ability of the vehicle to overcome terrain obstacles of, or caused by, hydrology. Figure 15 illustrates the general nature of the problem. The vehicle moves towards the hydrology type obstacle. The initial phase is as the vehicle's wheels drop down over the step. The break angle of the vehicle must be less than the break angle of the bank. The vehicle must have stability on the slope of the bank and the approach angle of the vehicle must be great enough to preclude the nose of the vehicle from burrowing into the stream bed. The vehicle must have a fording capability great enough to permit it to overcome the water depth. The final obstacle to overcome is the step height which must be less than the radius of the vehicle tires.

Streams are random factors and occur only upon occasion. Likewise, the obstacles created by streams are random and must be determined through statistical analysis. For the purposes of this study, a stream or hydrology type obstacle occurs once in every 200 vehicle lengths. The actual frequency within a given area may be less or it may be greater. For the purpose of this study, the above frequency is used.



s = step height
ω = break angle
θ = approach angle
d = water depth

Figure 15. General Nature of Hydrology Factors Influencing Vehicular Passage

To accomplish the above sequence of events, the flow chart for this sub-section is represented by Figure 16.

The facility is seized by the vehicle entering SEIZE block 500. Since only .005 of the vehicles are evaluated against hydrology .005 is the selection made for ADVANCE block 501. COMPARE blocks 506, 508, 510 and 512 evaluate the vehicle for break angle, approach angle, water depth, and step height, respectively. If the vehicle fails to negotiate any one of the COMPARE blocks, it returns to preceding ADVANCE which sends the vehicle to one of the ASSIGN blocks 525, 530, 535, or 540. These ASSIGN blocks place a 1, 2, 3, or 4, respectively, in parameter 4 to indicate which type of obstacle halted the vehicle. SAVEX block 545 stores the information for later use. The vehicle then moves to LOGIC block 560 where logic switch 4 is reset to 0. If the vehicle successfully passes through all COMPARE blocks it enters ASSIGN block 550 which counts success completions of Factor Family 4 Evaluation Sub-Section. This information is stored by SAVEX block 555 and the vehicle is released by RELEASE block 590.

Data Collection Section

The data collection section is represented in each evaluation sub-section by the ASSIGN and SAVEX blocks which store the successful number of passes by each vehicle in parameter 8. The data collection causes these values to be printed out for each vehicle by PRINT block 700, which is the value for Factor Family 2; PRINT block 701, which is the value for Factor Family 3; PRINT block 702, which is the value for Factor Family 4; and PRINT block 703, which is the value for Factor

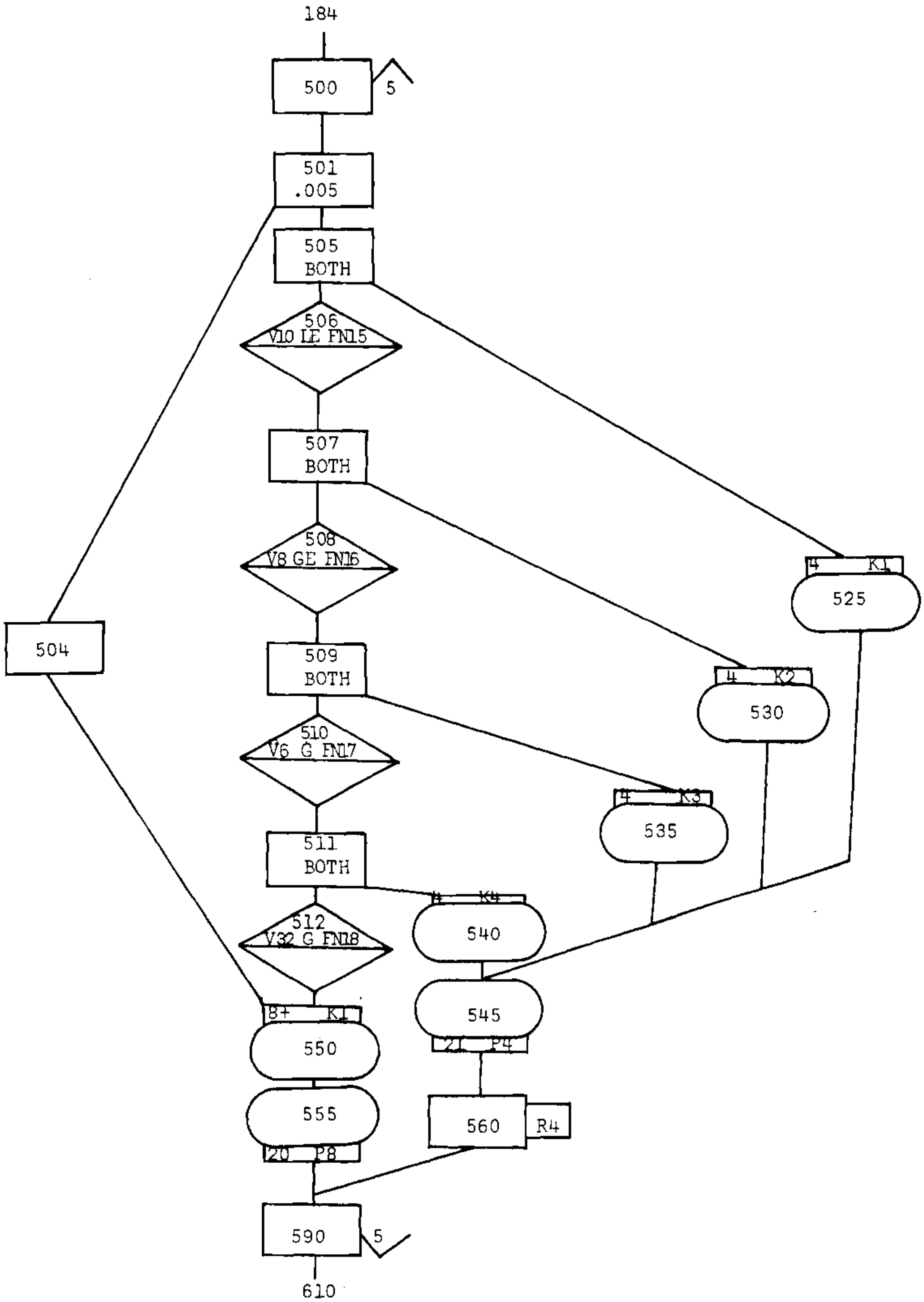


Figure 16. Factor Family 4 Evaluation Sub-Section Flow Chart

Family 1. PRINT block 704 prints out the type of obstacle, if any, that halted the vehicle in Factor Family 4.

CHAPTER V

DESIGN OF EXPERIMENTS

Introduction

The overall objective of this study was to provide the pulpwood producer with a means whereby a typical pulpwood harvesting vehicle could be evaluated. The accomplishment of this objective required initially the selection and design of a model to perform this evaluation. Previous chapters have served to present this result. This chapter deals with the design of the experiments performed using the computer simulation model which provides the pulpwood producer with the necessary information upon which to base his evaluation.

The most promising avenue of approach for the attainment of usable data appeared to be evaluation of an actual vehicle against actual terrain. Data were available for five pulpwood resource areas in the State of Georgia located in Gwinnett County, Chatham County, McIntosh County, Haralson County, and Telfair County (60). These data included the general nature of the terrain in sufficient detail that a reasonable facsimile could be constructed. The design specifications for the Taylor S-112 logging skidder were also obtained. This vehicle was used earlier in an actual experiment by Freitag and Richardson (61). The resulting empirical data permitted validation of the model. The Taylor S-112 has several options, one of which is tire size. This option of tire sizes permitted the vehicle to be evaluated at two levels.

The Experiment

Two experimental designs evolved from the requirements of the producer. The first requirement was to determine with a probability, the percentage of resource areas that the producer could harvest prior to his vehicle being overcome by terrain obstacles. Five pulpwood resource areas were considered as a selective sample of a total of 35 pulpwood resource areas that the pulpwood producer expected to harvest over the next year. This experiment consisted of estimating the mean and variance of the distance the vehicle travelled until halted by an obstacle for each of the five resource areas considered.

By using the Student's t-distribution in the manner suggested by Hicks (62), the mean and variance of each area were determined. In this method, variance is determined by using the mean square for error of the analysis of variance divided by the number of replications performed. The square root of this value is multiplied by a t value which is gotten out of a standardized table. The resulting value is the deviation which, in this experiment, is subtracted from the average distance travelled to provide a lower limit that the producer may expect his vehicle to travel within the specified area prior to being overcome by terrain obstacles. The values obtained in this experiment are listed in Chapter VI by each area.

The second requirement was to determine if a difference existed in the performance of the pulpwood harvesting vehicle caused by selection of optional tire sizes. The experimental design employed to test this hypothesis was a two-factor design with two levels of vehicle effects and five levels of terrain effects. The analysis of variance was utilized to formally test two hypotheses: (1) that there was no effect caused by terrain, and (2) that there was no difference in performance caused by changing the tire size. An analysis of variance table with illustrative data is shown as Table 1.

Table 1. ANOVA Table with Illustrative Values

Source	df	ss	ms
Areas	4	400	100
Tires	1	100	100
Interaction	4	400	100
Error	240	2400	10
Total	249	3300	

The number of replications to be performed in the experiments was determined through the method demonstrated by Bowker and Lieberman (63). Here, a level of significance for rejecting a true hypothesis is chosen, in this case, the value was .05. The appropriate figure is chosen from several possible on the basis of this level of significance. Two other values are then required to read from the figure. These values are the acceptable risk of failing to reject a hypothesis and the deviation from the true mean that is to be detected. Since no knowledge of the true standard deviation existed a value of 50 was chosen. It was desired to detect a 10 per cent shift in the true means with a .95 probability. A risk of .10 was considered acceptable in failing to reject a false hypothesis. All of these values combined on the figure to give a result of about 25 replications.

Derivation of Data

The five terrain areas were assumed to be representative of the 35 areas to be harvested. Each area's terrain characteristics were placed into functions for evaluation against the test vehicle's characteristics. For each area, there were ten functions to be described. These functions are described for each area in Figures 17 to 21, respectively. Because the terrain was almost identical in area 4 and area 5, it was assumed that the hydrology obstacles in area 5 were bridged. The same assumption was also made for area 1 and area 3 due to their similarity. Functions exactly duplicated in Figures 17 to 21 are not repeated for the respective following terrain areas.

The determination of the function values for area 1 is discussed in detail. Where significantly different, the values of functions for the other areas will be discussed. Because no real distributions were available the values were, in the main, selected as being reasonable.

FUNCTION 2 is the distribution of the soil cone indexes. The values used in this function were approximations for sandy loam. Bassett *et al.* (64) obtained values for a loess soil which gave a general idea as to the nature of the soil distribution.

FUNCTION 4 is the slope of the area. The available data provided either the exact slope of the area or a grouping of values within 5 per cent tolerances.

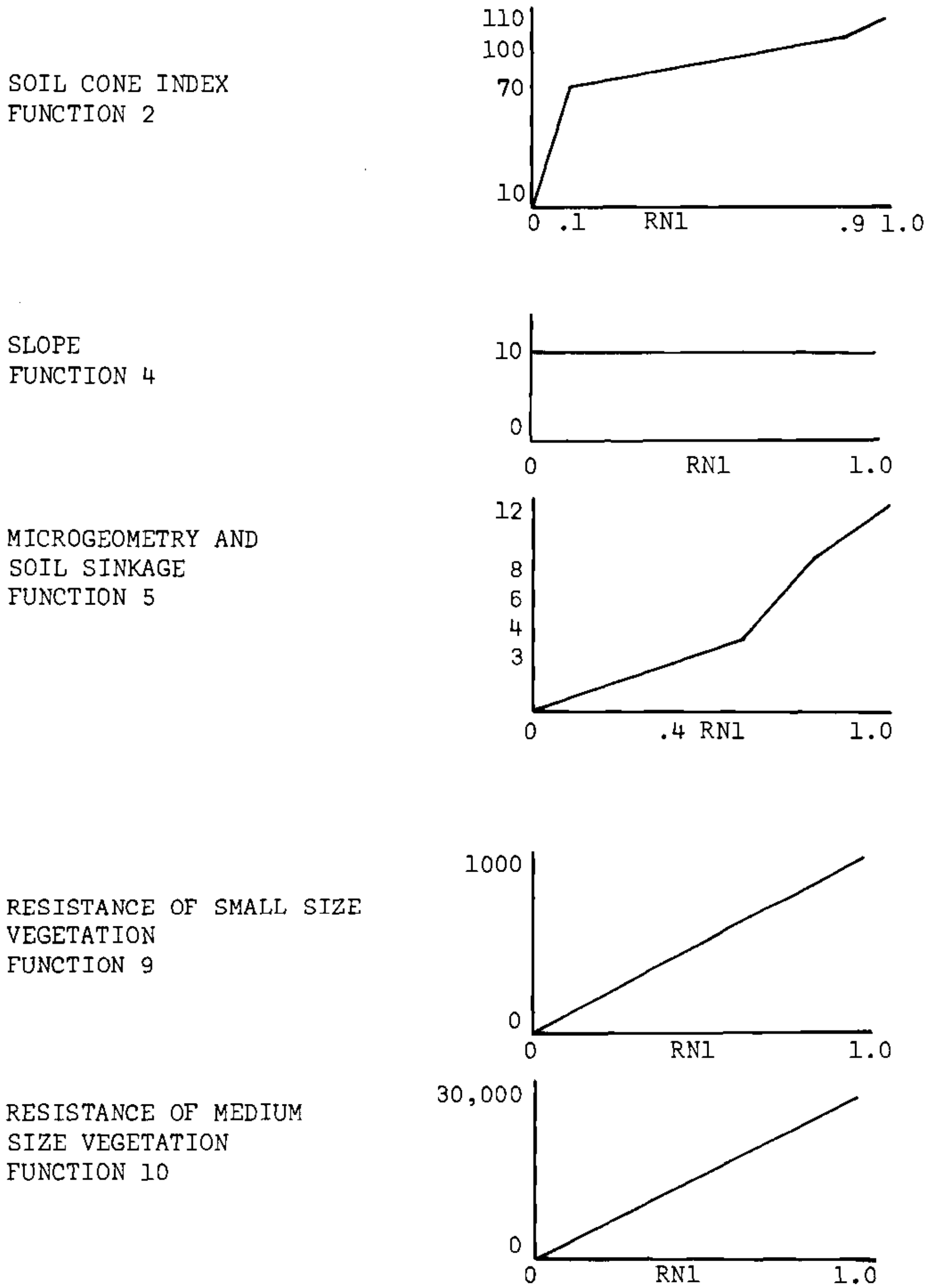
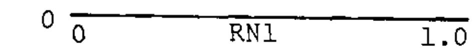
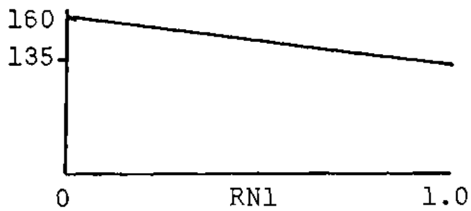


Figure 17. FUNCTION Values for Area 1
[Data Provided by American
Pulpwood Association]

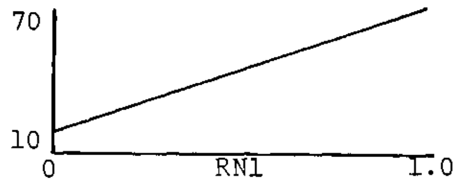
RESISTANCE OF LARGE SIZE
VEGETATION
FUNCTION 11



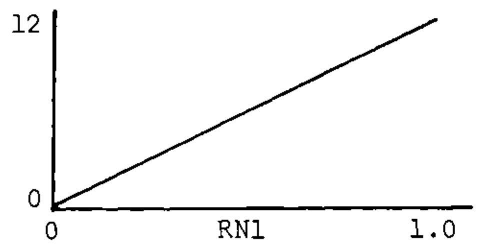
GROUND BREAK ANGLE
FUNCTION 15



APPROACH ANGLE
FUNCTION 16



WATER DEPTH
FUNCTION 17



STEP HEIGHT
FUNCTION 18

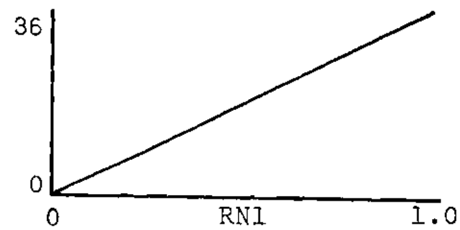


Figure 17. FUNCTION Values for Area 1 (Continued)
[Data provided by American Pulpwood Association]

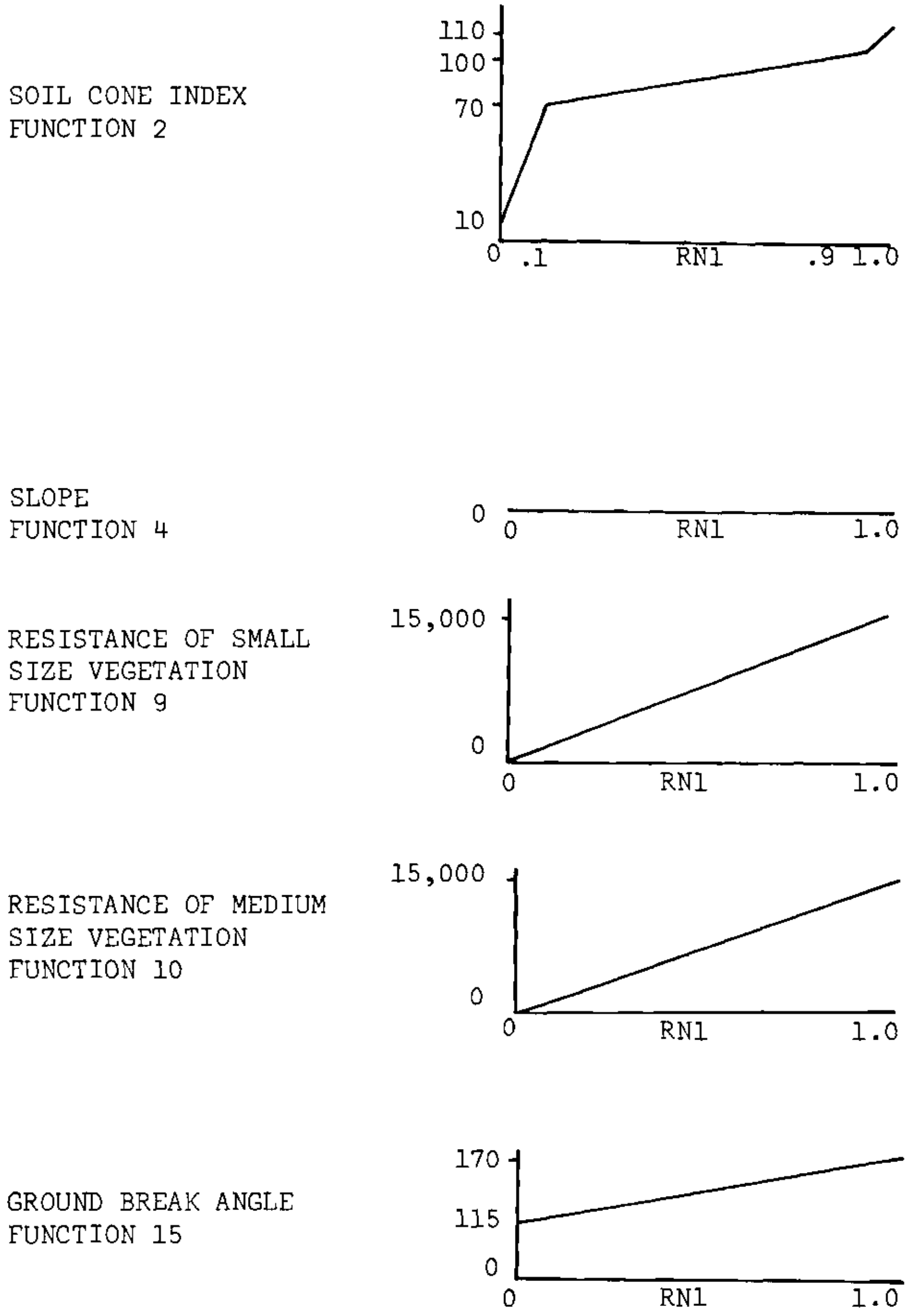
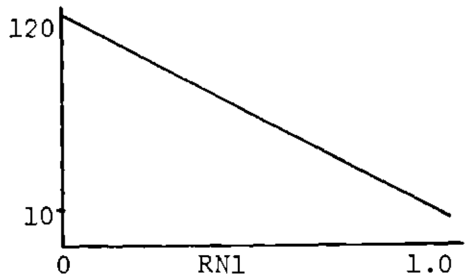
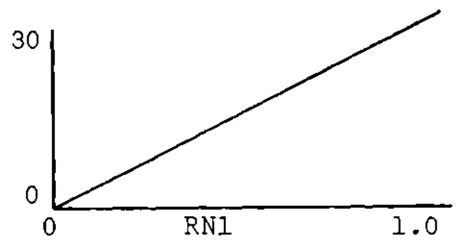


Figure 18. FUNCTION Values for Area 2 [Data Provided by American Pulpwood Association]

APPROACH ANGLE
FUNCTION 16



WATER DEPTH
FUNCTION 17



STEP HEIGHT
FUNCTION 18

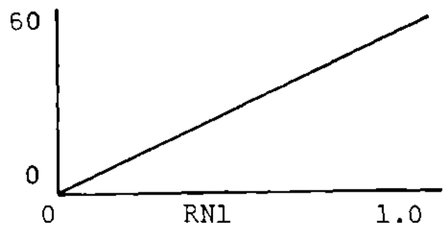


Figure 18. FUNCTION Values for Area 2 (Continued)
[Data Provided by American Pulpwood Assn.]

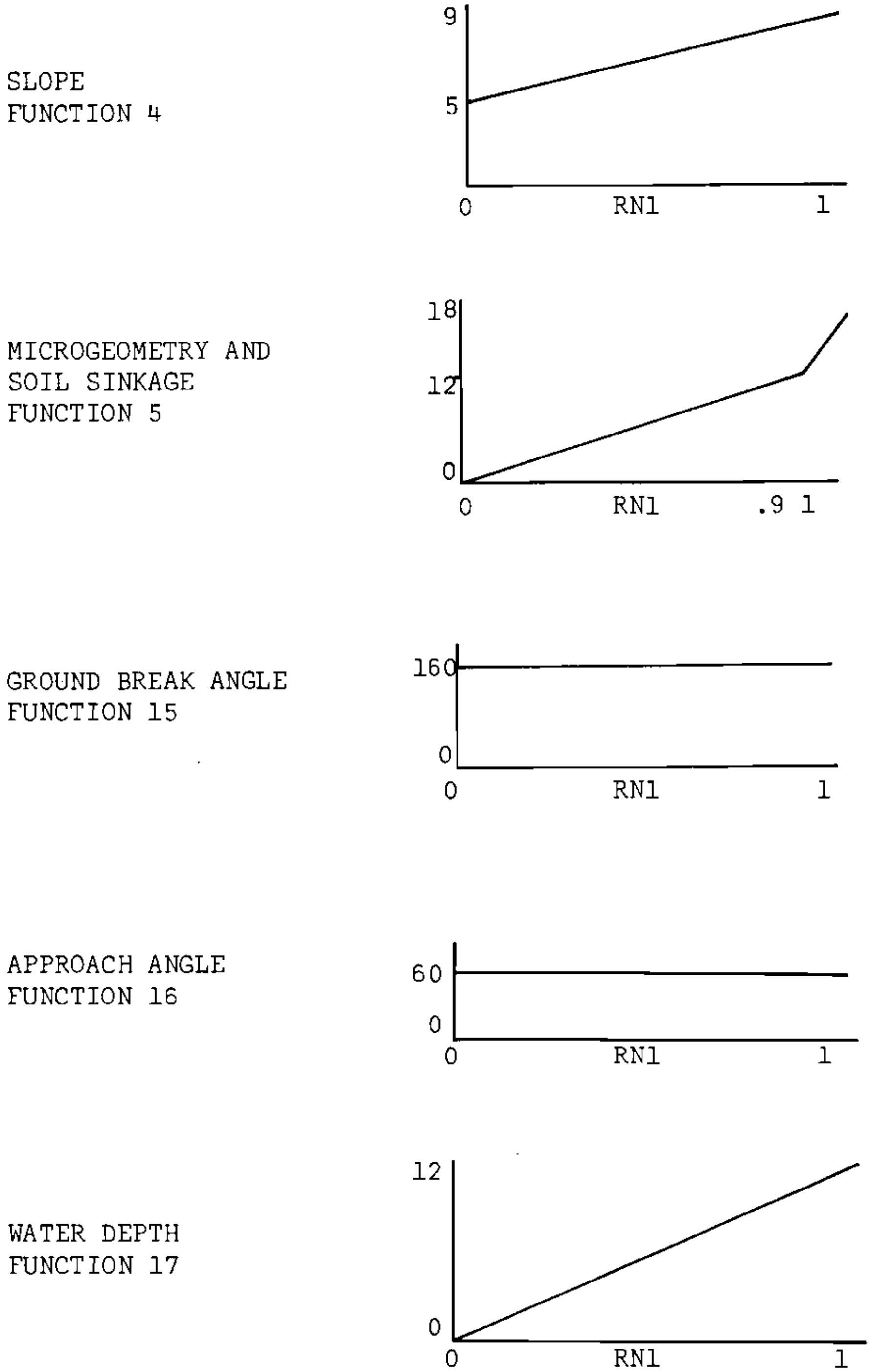
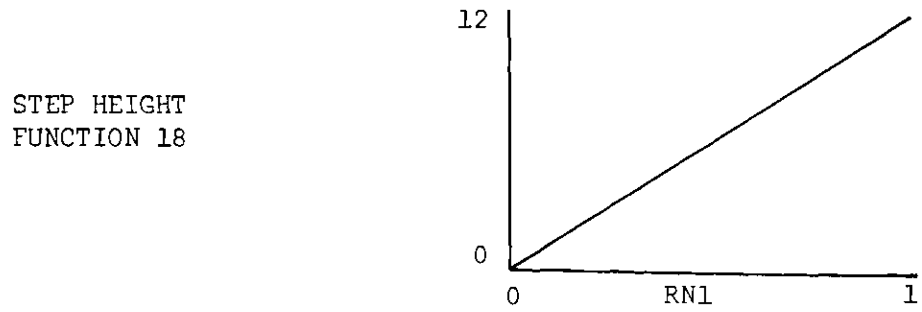


Figure 19. FUNCTION Values for Area 3 [Data Provided by American Pulpwood Association]



Function 19. FUNCTION Values for Area 3 (Continued)
[Data Provided by American Pulpwood Assn.]

FUNCTION 5 is microgeometry and soil sinkage. These values were taken from data on the five resource areas. The data gave the stoniness of the ground in terms of rocks greater than 12 inches high covering a percentage of the total ground. Ground roughness was given in qualitative terms. From the percentage figure on stoniness and the qualitative description of ground roughness, a reasonable distribution was assumed for each area.

The available data provided the number of trees per acre and a qualitative description of the brush. The data were not available to determine the bending moment for trees and brush. Values were again assumed for FUNCTIONs 9, 10, and 11. These values are relative to one another only for illustrative purposes.

The values for FUNCTIONs 15, 16, 17, and 18 came from the work performed on the Ranger training areas by the University of Tennessee (65). The assumption made here was that hydrology type obstacles would be similar within each broad area classification.

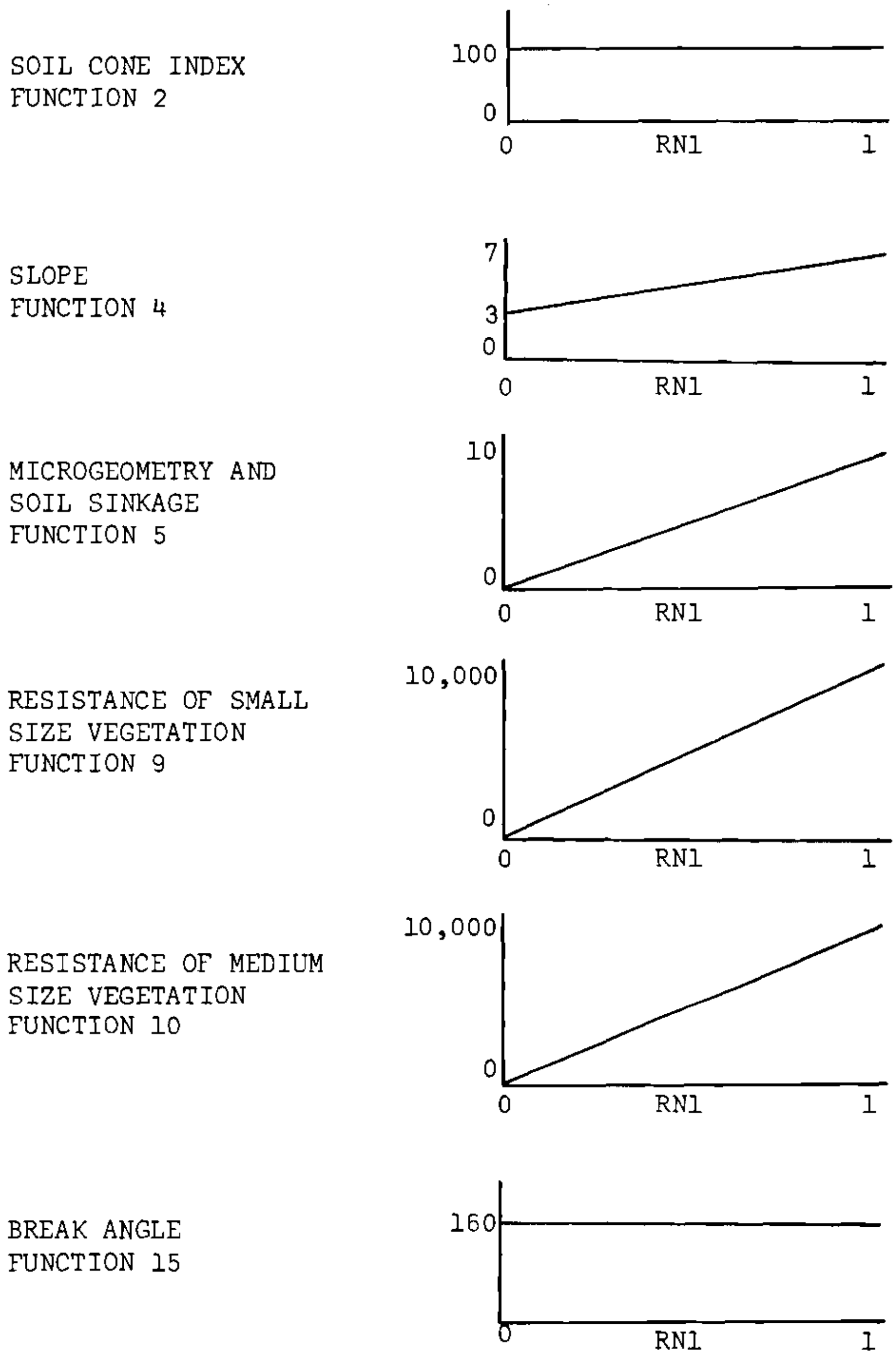
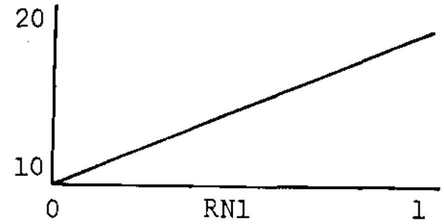
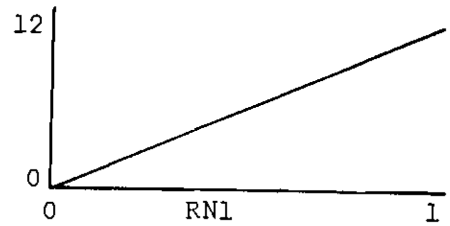


Figure 20. FUNCTION Values for Area 4 [Data Provided by American Pulpwood Association]

APPROACH ANGLE
FUNCTION 16



WATER DEPTH
FUNCTION 17



STEP HEIGHT
FUNCTION 18

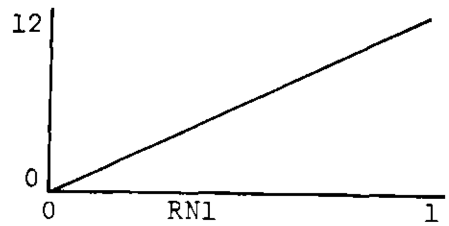


Figure 20. FUNCTION Values for Area 4 (Continued) [Data Provided by American Pulpwood Association]

These classifications were Piedmont, Upper Coastal Plain, and Lower Coastal Plain. The distribution chosen was a straight line from the smallest value to the greatest value.

The disadvantage of this particular experimental input was that it immediately became apparent that the five areas were generally similar. For this reason it was decided to conduct one experiment containing significant differences in one factor family for each area.

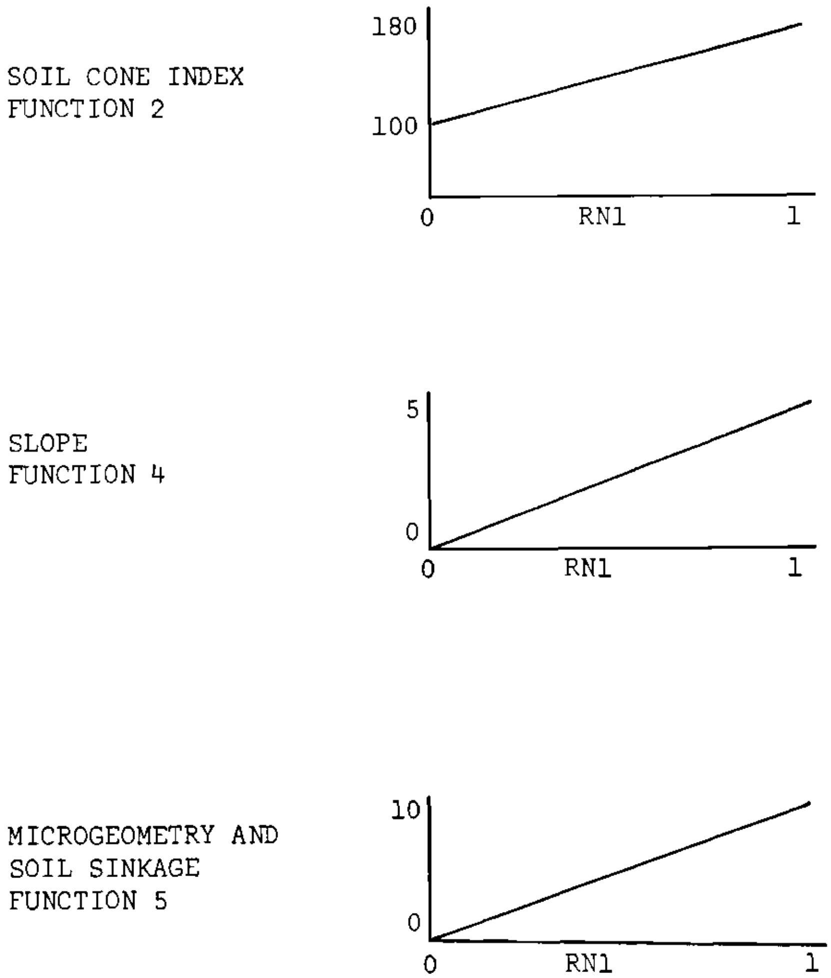
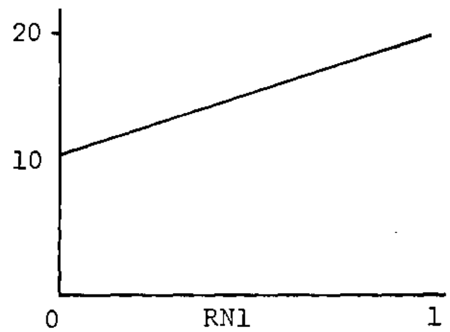


Figure 21. FUNCTION Values for Area 5 [Data Provided by American Pulpwood Association]

The new functions and the areas in which they were placed are shown as Figures 22 to 26. While not totally related to the actual areas, this new experiment would give an indication of the sensitivity of the computer simulation model.

SLOPE
FUNCTION 4



MICROGEOMETRY AND
SOIL SINKAGE
FUNCTION 5

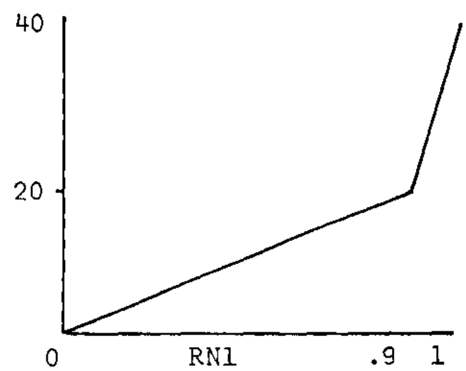
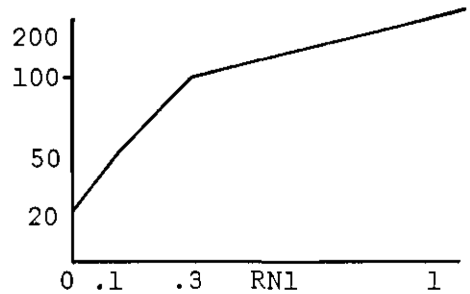
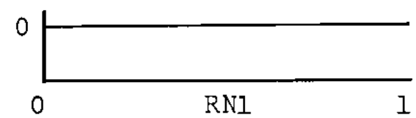


Figure 22. Sensitivity Values for Area 1
[Assumed Data]

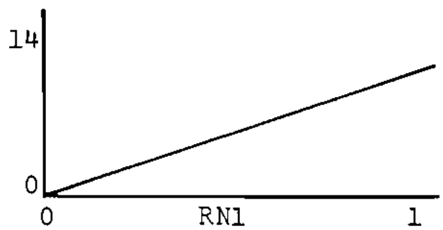
SOIL CONE INDEX
FUNCTION 2



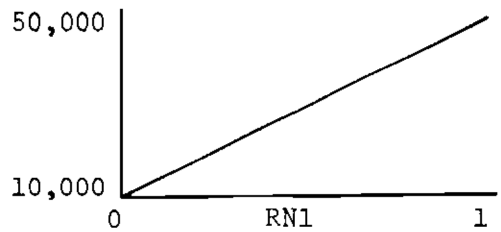
SLOPE
FUNCTION 4



MICROGEOMETRY AND
SOIL SINKAGE
FUNCTION 5



RESISTANCE OF SMALL
SIZE VEGETATION
FUNCTION 9



RESISTANCE OF MEDIUM
SIZE VEGETATION
FUNCTION 10

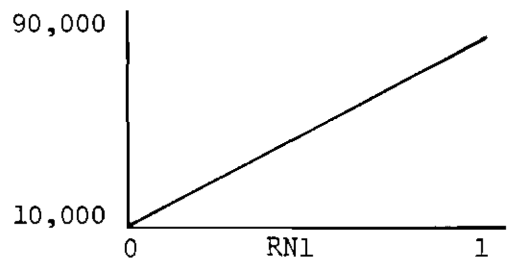
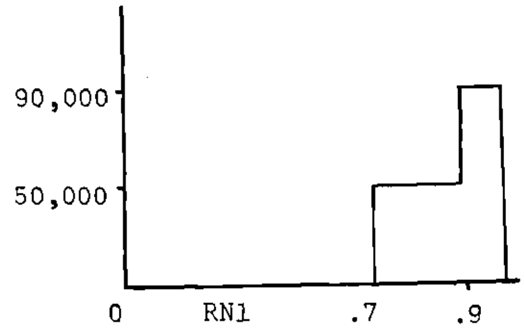
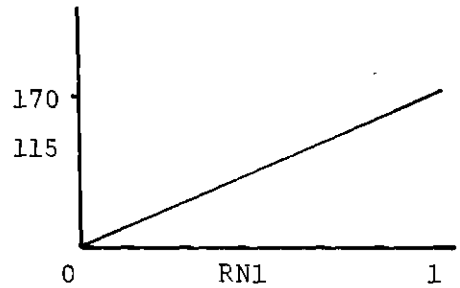


Figure 23. Sensitivity Values for Area 2
[Assumed Data]

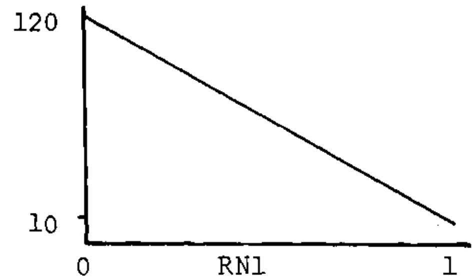
RESISTANCE OF LARGE
SIZE VEGETATION
FUNCTION 11



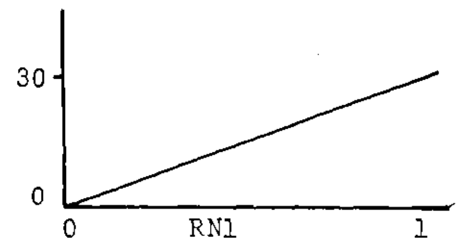
BREAK ANGLE
FUNCTION 15



APPROACH ANGLE
FUNCTION 16



WATER DEPTH
FUNCTION 17



STEP HEIGHT
FUNCTION 18

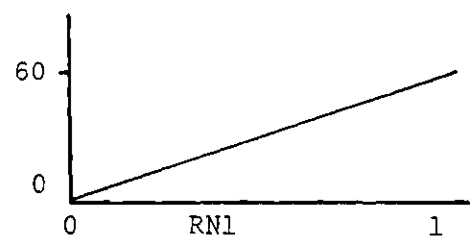


Figure 23. Sensitivity Values for Area 2 (Continued)
[Assumed Data]

SOIL CONE INDEX
FUNCTION 2

SLOPE
FUNCTION 4

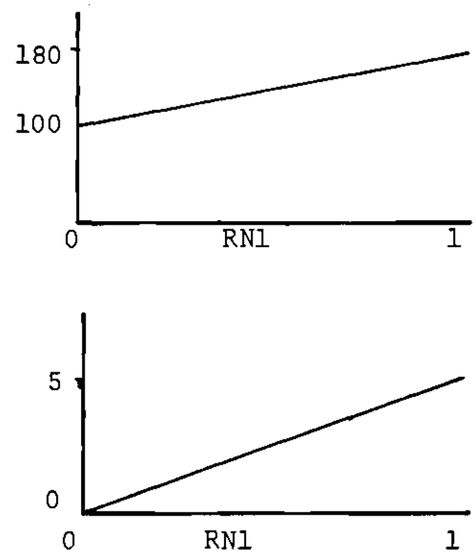
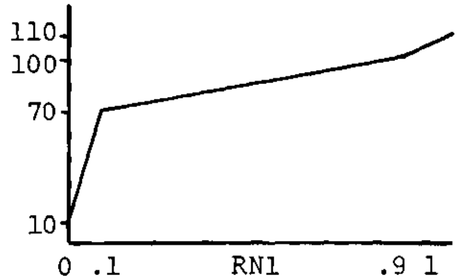
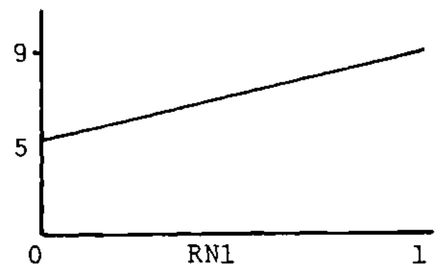


Figure 24. Sensitivity Values for Area 5 [Assumed Data]

SOIL CONE INDEX
FUNCTION 2



SLOPE
FUNCTION 4



MICROGEOMETRY AND
SOIL SINKAGE
FUNCTION 5

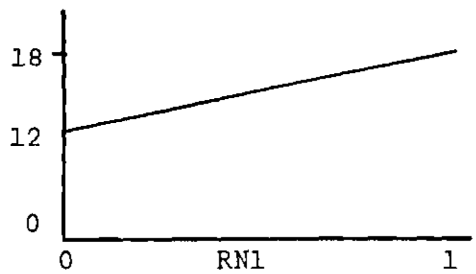


Figure 25. Sensitivity Values for Area 3 [Assumed Data]

SOIL CONE INDEX
FUNCTION 2

SLOPE
FUNCTION 4

MICROGEOMETRY AND
SOIL SINKAGE
FUNCTION 5

RESISTANCE OF SMALL
SIZE VEGETATION

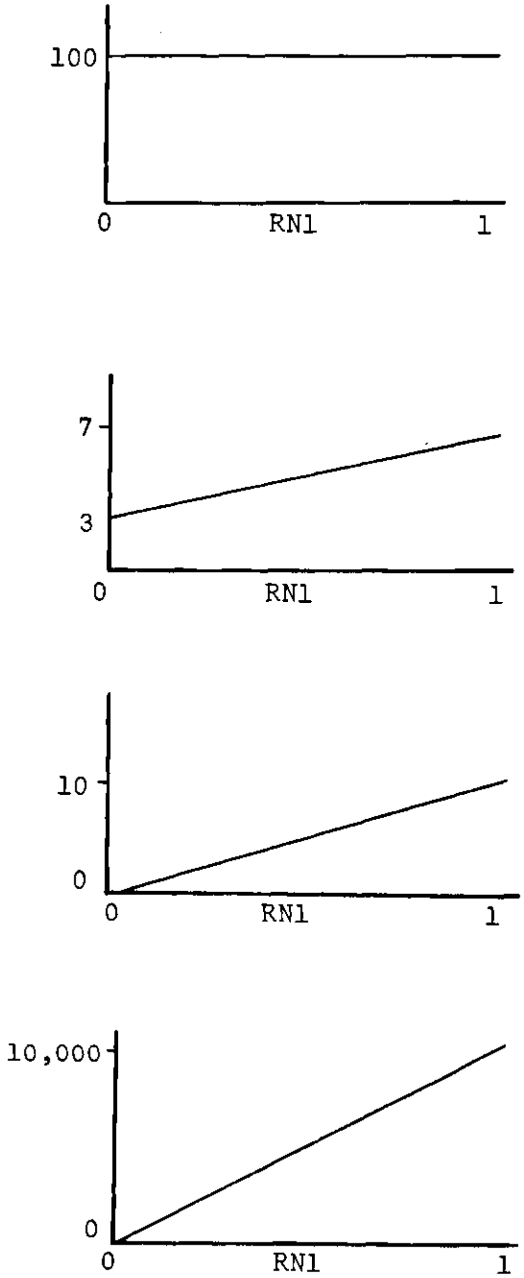
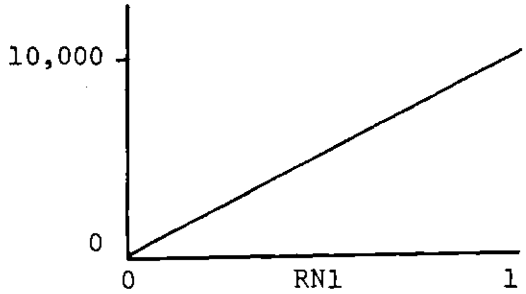
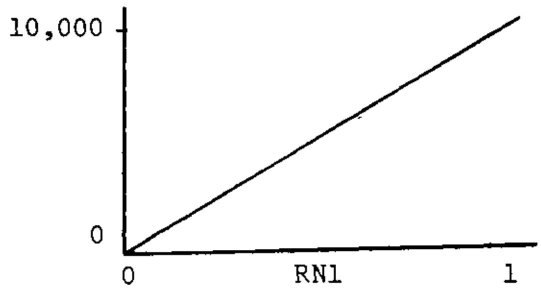


Figure 26. Sensitivity Values for Area 4
[Assumed Data]

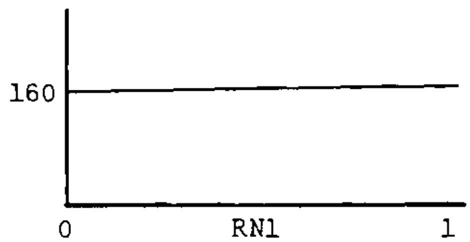
RESISTANCE OF MEDIUM
SIZE VEGETATION
FUNCTION 10



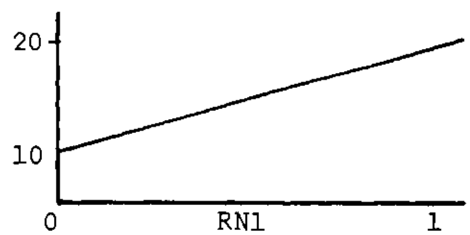
RESISTANCE OF LARGE
SIZE VEGETATION
FUNCTION 11



BREAK ANGLE
FUNCTION 15



APPROACH ANGLE
FUNCTION 16



WATER DEPTH
FUNCTION 17

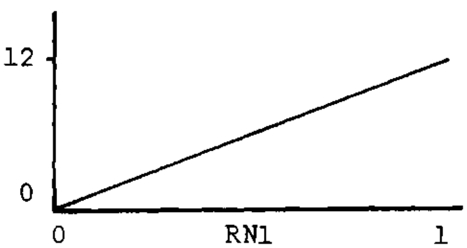


Figure 26. Sensitivity Values for Area 4 (Continued)
[Assumed Data]

CHAPTER VI

RESULTS, CONCLUSIONS, AND RECOMMENDATIONS

General

The nature of the results indicated that the computer simulation model performed as expected and provided data in a usable form. The analysis of variance indicated that the effects tested were statistically significant. A statistically significant difference in vehicle performance attributable to optional equipment was also detected.

Results

Experiment 1 used models of actual pulpwood resource areas as the terrain values against which the vehicle was to be evaluated for a measure of effectiveness. Following the computer simulation runs, an analysis of variance was conducted to determine if there was a significant difference in vehicle performance. The ANOVA table is shown as Table 2.

Table 2. ANOVA Table for Experiment 1

Source	df	ss	ms
Areas	4	80962	20240
Tires	1	27521	27521
Interaction	4	22535	5634
Error	240	991651	4132
Totals	249	1122669	

Using as the initial hypothesis, that there was no difference between the areas, the appropriate F ratio was $F_{4,240} = 4.898$ which was highly significant and the hypothesis was rejected. The second hypothesis was that there was no effect caused by the tire size. Here the corresponding F ratio was $F_{1,240} = 6.66$ which was highly significant and this hypothesis was also rejected. Thus the results of Experiment 1 lead us to conclude that there was a significant difference in the performance of the vehicle attributable to the areas to be harvested and the tire sizes.

To provide the producer with the information he requires, the method suggested by Hicks (66) as described in Chapter V was used. Here it was desired to state that the vehicle could negotiate x percentage of the terrain before being overcome by a terrain obstacle. The lower confidence level for this one-sided test was set at .95. This confidence level resulted in the following percentages:

Table 3. Lower Confidence Limits of Percent of Terrain Vehicle Can Negotiate

18.1 x 26 Tire Size	23.4 x 34 tire size
Area 1 75%	Area 1 89%
Area 2 78%	Area 2 90%
Area 3 81%	Area 3 86%
Area 4 94%	Area 4 94%
Area 5 94%	Area 5 94%

Stated in terms of the total of all five areas, the larger size tire would permit the vehicle to cover 91 per cent of each area without failure whereas the smaller size tire would only permit 85 per cent coverage. The individual producer could also see that no advantage existed for the larger tire in areas 4 and 5 and that the smaller tire (cheaper in price) would be entirely satisfactory.

The results of Experiment 2 were analyzed using the analysis of variance treatment as applied to the results of Experiment 1. The ANOVA table for Experiment 2 is shown below as Table 4.

Table 4. ANOVA Table for Experiment 2

Source	df	ss	ms
Areas	4	5821642	1455410
Tires	1	107	107
Interaction	4	347	87
Error	240	287128	1196
Total	249	6109224	

Again proposing the hypothesis of no area effect, the F ratio is 1217 which is highly significant. The hypothesis of no tire effect provides a ratio of less than 1 which is not significant. The first hypothesis is thus rejected and the second accepted. These results were not surprising when it is considered that the terrain portrayed was difficult to a degree that neither vehicle possessed the ability to overcome the obstacles. Hence, in order to harvest these areas, the producer would have to either extensively modify the terrain or use an entirely different vehicle. In extreme cases both actions might be required.

The results of the experiments conducted demonstrated the feasibility of a computer simulation model to predict the ability of a vehicle to negotiate terrain. From these results certain conclusions can be drawn.

Conclusions

It became obvious early in the conduct of the experiments that hydrology type obstacles dominated the relationship between the pulpwood harvesting vehicle and the terrain over which it passed. This domination could be significantly reduced by modification of the obstacle prior to the pulpwood harvesting vehicle encountering it.

The actual pulpwood resource areas presented in this digital computer simulation model did not present difficult obstacles to the pulpwood harvesting vehicle modelled. With the elimination of hydrology type obstacles, the pulpwood harvesting vehicle had almost complete freedom of movement within the resource areas.

The Upper Coastal Plain areas, such as Telfair County, presented no obstacles to the pulpwood harvesting vehicle. While the effect of moisture was not considered in this model, it is possible that the soil cone index in this area would not be adversely affected to a significant degree due to the somewhat sandy nature of the soil.

The pulpwood harvesting vehicle, presently in use, is more than adequate for the five listed areas in Georgia.

The model, as constructed, provides the individual pulpwood producer with a means of determining the percentage of his pulpwood resource areas, subject to the assumptions heretofore described and the specific areas chosen, that can be harvested by a specific item of equipment provided with a specified tire size.

The model is valid for evaluating vehicle performance within the areas normally worked by a pulpwood producer. If significant changes in terrain do exist within a 25-mile radius of the producer's base of operations then this model should be modified to reflect the change in terrain.

Recommendations

The assumption of three vehicle lengths being required to halt the vehicle fails to consider the extreme differences in wheelbase between large and small vehicles. It is recommended that this model be expanded to consider soft soil strictly as a function of distance rather than as a specified number of wheelbase lengths.

A statistical treatment of vegetation should be conducted to permit the expansion of this model to include true vegetation resistance rather than assumed values.

Vehicle speed as a function of obstacles and rolling resistance should be brought into this model. This expansion would permit a more refined cost analysis of a vehicle's performance on a basis of time required per acre.

Further research should consider performance evaluations of vehicles with modifications designed to reduce the problem of hydrology type obstacles which demonstrated such an adverse effect on vehicle mobility.

A cost analysis should be performed on present rubber-tired skidders operating in the Piedmont and Upper Coastal Plain regions. This analysis would be to determine if the pulpwood harvester requires the mobility of the skidder when a less costly vehicle might well be adequate.

APPENDIX

APPENDIX A

MOBILITY INDEX CALCULATIONS

FOR TAYLOR S-112

<u>23 x 34 Tire Size</u>

$$MI = \left(\frac{\text{contact pressure factor} \times \text{weight factor}}{\text{tire factor} \times \text{grouser factor}} + \text{Wheel Load Factor} - \text{Clearance Factor} \right) \times \text{Engine Factor} \times \text{Transmission Factor}$$

Vehicle Factor	Value

Contact Pressure Factor $= \dfrac{\text{Gross Weight, Lb.}}{\text{Nom. Tire Width, In.} \times \dfrac{\text{Outside Diam. Tire, In.}}{2} \times \text{No. of Tires}}$

$\dfrac{16{,}495}{23.1 \times 62.5/2 \times 4}$ = 5.71

Weight Factor:	Weight Range (Lbs/Axle)	Weight Factor Equation	
	2,000 to 13,500	Y = 0.033X + 1.050 X = Gross wt in kips/axle	
	Y = 0.033(8.25) - 1.05		= 1.32
Tire Factor:	$\dfrac{10 + \text{tire width, in.}}{100} = \dfrac{10 + 23.1}{100}$		= 0.33
Grouser Factor:	Without Chains = 1.00		= 1.00
Wheel Load Factor:	$\dfrac{\text{Gross Weight (Kips)}}{\text{No. of Wheels}} = \dfrac{16.50}{4}$		= 4.12
Clearance Factor:	Clearance Factor $= \dfrac{\text{Clearance, In.}}{10}$		= 2.10
Engine Factor:	710 hp/ton = 1.00		= 1.00

Vehicle Factor (Continued)	Value
Transmission Factor: Hydraulic = 1.00	= 1.00
$MI = \left(\frac{5.71 \times 1.32}{0.33 \times 1.00} + 4.12 - 2.10\right) \times 1.00 \times 1.00$	= $\underline{25}$

<u>18 x 26 Tire Size</u>

Vehicle Factor	Value
Contact Pressure Factor = $\frac{16,495}{18.4 \times 54/2 \times 4}$	= 8.3
Weight Factor:	= 1.32
Tire Factor: $\frac{10 + 18.4}{100}$	= 0.28
Grouser Factor:	= 1.00
Wheel Load Factor:	= 4.12
Clearance Factor: $\frac{17}{10}$	= 1.7
Engine Factor:	= 1.00
Transmission Factor:	= 1.00
$MI = \left(\frac{8.3 \times 1.32}{.28 \times 1.00} + 4.12 - 1.7\right) \times 1.0 \times 1.0$	= $\underline{42}$

APPENDIX B

PROGRAM LISTING

```
LOC  NAME          X       Y       Z      SEL    NBA    NBB    MEAN   MOD    REMARKS     E

     JOB
************************************************************************
************************************************************************
*THE DECK CONTAINS FUNCTION VALUES  FOR SENSITIVITY ANALYSIS OF THE PROGRAM
************************************************************************
*
*    SIMULATION MODEL TO EVALUATE MOBILITY IN CONVENTIONAL GROUND VEHICLES
*
************************************************************************
************************************************************************
*
*DECK ONE
************************************************************************
************************************************************************
*    VARIABLES TO BE DEFINED
*
************************************************************************
 1   VARIABLE     K108                                          WHEEL BASE
 2   VARIABLE     K130                                          HORSEPOWER
 3   VARIABLE     K62                                           WHEEL SIZE
 4   VARIABLE     K218                                          LENGTH
 5   VARIABLE     K21                                           GRND CLEARANCE
 6   VARIABLE     K43                                           HGT OF C.G.
 7   VARIABLE     K76                                           VEHICLE TRACK
 8   VARIABLE     K90                                           APPROACH ANGLE
 9   VARIABLE     K100                                          DEPARTURE
*                                                               ANGLE
10   VARIABLE     K145                                          BREAK ANGLE
11   VARIABLE     K2                                            SUSPENSION
12   VARIABLE     K1                                            FLOTATION
13   VARIABLE     K92                                           TURNING RADIUS
14   VARIABLE     K23                                           TIRE WIDTH
15   VARIABLE     K16495                                        WEIGHT
16   VARIABLE     K4                                            NO. OF TIRES
22   VARIABLE     K2                                            NO. OF AXLES
28   VARIABLE     K100                                          TRANS. FACTOR
31   VARIABLE     K36000/V1+K3                                  NUMBER OF
*                                                               LOOPS
33   VARIABLE     V15/V22                                       AXLE LOAD
41   VARIABLE     K12000                                        DRAWBAR PULL
*TRACTIVE EFFORT OF WHICH THE VEHICLE IS CAPABLE
************************************************************************
*
*
*
*
*
*
*
************************************************************************
*
*
************************************************************************
```

```
*
*    GWINNETT COUNTY - AREA ONE
*
**********************************************************************************
*THIS FUNCTION GIVES THE DISTRIBUTION OF SOIL CONE INDEXES
 2     FUNCTION     RN1     C4
0      10     .1     70     .9     100     1.0     110
* THIS FUNCTION DEFINES THE MAJOR SLOPE GROUPING
 4     FUNCTION     RN1     C2
0      10     1.0     20
*  THIS FUNCTION DEFINES THE MICROGEOMETRY AND SOIL SINKAGE
 5     FUNCTION     RN1     C3
0      0     .9     20     1.0     40
*THIS FUNCTION DEFINES THE RESISTANCE OF THE SMALL VEGETATION TO THE VEHICLE
*THE NUMBERS IN THE FUNCTION ARE FOR A 360INCH BY 360INCH AREA
 9     FUNCTION     RN1     C2
0      0     1.0     1000
*THIS FUNCTION DEFINES THE RESISTANCE OF THE MEDIUM SIZED VEGETATION.
 10    FUNCTION     RN1     C2
0      0     1.0     30000
*THIS FUNCTION DEFINES THE RESISTANCE OF THE LARGE SIZED VEGETATION
 11    FUNCTION     RN1     C2
0      0     1.0     0
*THIS FUNCTION DEFINES THE BREAK ANGLE
 15    FUNCTION     RN1     C2
0      160     1.0     135
*THIS FUNCTION DEFINES THE APPROACH ANGLE
 16    FUNCTION     RN1     C2
0      10     1.0     70
*THIS FUNCTION DEFINES WATER DEPTH
 17    FUNCTION     RN1     C2
0      0     1.0     12
*THIS FUNCTION DEFINES STEP HEIGHT
 18    FUNCTION     RN1     C2
0      0     1.0     36
*
*
*    THE MODEL BEGINS
*
*
**********************************************************************************
 100  GENERATE     1                              111          1
**********************************************************************************
 30   VARIABLE     K25                                                MOBILITY INDEX
**********************************************************************************
*    MOBILITY INDEX VERSUS VEHICLE CONE INDEX
 1    FUNCTION     P2     C5
0     0     25     10     50     20     150     30     1650     100
*
**********************************************************************************
 111  GATE         NU1                            112
 112  ASSIGN       6      K3                      115
 115  ASSIGN       3      V31                     120
**********************************************************************************
 120  LOGIC        S1                             121
 121  LOGIC        S2                             122
 122  LOGIC        S3                             123
```

```
 123  LOGIC         S4                               124
*************************************************************************
 124  ASSIGN        8      K1                        160
 160  ASSIGN        2      V30                       180
*************************************************************************
*
*
*************************************************************************
*************************************************************************
*
*     THE VEHICLE HAS NOW BEEN DEFINED AND ITS CHARACTERISTICS ASSIGNED AS
*     PARAMETERS THE VEHICLE NOW ENTERS THE TEST TRACK FOR EVALUATION
*
*************************************************************************
*************************************************************************
 180  SEIZE         1                                182                    TRACK
 182  SPLIT                                          183    184
 183  SPLIT                                          200    300
 184  SPLIT                                          400    500
*************************************************************************
*************************************************************************
*************************************************************************
 200  SEIZE         2                                205                    FACTOR FAMILY1
*THIS FACTOR FAMILY COMPARES THE SOIL CONE INDEX AGAINST THE MOBILITY INDEX
*OF THE VEHICLE BEING EVALUATED
*************************************************************************
*
*************************************************************************
 35   VARIABLE      X1+X2+X3                                                SUM
 36   VARIABLE      V35/K3                                                  AVERAGE OF 3
*                                                                           SOIL CONE
 205  SAVEX         3      X2                        206                    CONE INDEX 3
 206  SAVEX         2      X1                        207                    CONE INDEX 2
 207  SAVEX         1      FN2                       208                    CONE INDEX 1
*THE CONE INDEX OF THE SOIL IS GENERATED BY A RANDOM NUMBER IN THESE BLOCKS
*FOR COMPARISON WITH THE MOBILITY INDEX OF THE VEHCCLE
 208  SAVEX         4      V36                       209
 209  ADVANCE                                        210
*
*************************************************************************
 210  ADVANCE                              BOTH      212    214
 212  COMPARE       P6     E       K0                215
 214  LOOP          6                                205    215
 215  ADVANCE                              BOTH      220    225
 220  COMPARE       FN1    L       V36               221
 221  ASSIGN        8+     K1                        222
 222  SAVEX         10     P8                        290
 225  LOGIC         R1                               290
 290  RELEASE       2                                600
*************************************************************************
*************************************************************************
*************************************************************************
 300  SEIZE         3                                301                    ENTERING
*FACTOR FAMILY 2--SLOPE AND MICROGEOMETRY
*THE SLOPE OF THE GROUND IS GIVEN BY FUNCTION 4  WHICH IS ASSIGNED TO THE MODEL
*AS PARAMETER 5
*THE EFFECT OF THE MICROGEOMETRY IS COMPUTED IN VARIABLES
```

```
*THE VARIABLES LISTED BELOW COMPUTE THE STABILITY OF THE VEHICLE
**********************************************************************
 46    VARIABLE    FN6+K10000/V7*P7
 47    VARIABLE    V6*P4                                              CG SINE OMEGA
 49    VARIABLE    V7*FN8/K2                                          1/2TCOS OMEGA
**********************************************************************
*  THIS FUNCTION DEFINES THE SINE OF ANGLES BETWEEN 0 AND 45 DEGREES
 6     FUNCTION    P5    D46
0      0     1     1750  2     3490  3     5230  4     6980  5     8720
6      1045  7     1219  8     1392  9     15644 10    1736  11    1908
12     2079  13    2250  14    2419  15    2588  16    2756  17    2924
18     3090  19    3256  20    3420  21    3584  22    3746  23    3907
24     4067  25    4226  26    4384  27    4540  28    4695  29    4848
30     5000  31    5150  32    5299  33    5346  34    5565  35    5736
36     5878  37    6018  38    6157  39    6293  40    6428  41    6561
42     6691  43    6820  44    6947  45    7071
**********************************************************************
*  THIS FUNCTION DEFINES THE COSINES OF ANGLES BETWEEN 0 AND 45 DEGREES
 7     FUNCTION    P5    D46
0      1.0   1     9998  2     9994  3     9986  4     9976  5     9962
6      9945  7     9925  8     9903  9     9877  10    9848  11    9816
12     9781  13    9744  14    9703  15    9659  16    9613  17    9563
18     9511  19    9455  20    9397  21    9336  22    9272  23    9205
24     9135  25    9063  26    8988  27    8910  28    8829  29    8746
30     8660  31    8572  32    8480  33    8387  34    8290  35    8192
36     8090  37    7986  38    7880  39    7771  40    7660  41    7547
42     7431  43    7314  44    7193  45    7071
**********************************************************************
*THIS FUNCTION CONVERTS SINES TO COSINES DIRECTLY
 8     FUNCTION    P4    D46
0      10000 175   9999  349   9994  523   9986  698   9976  872   9962
1045   9945  1291  9925  1392  9903  1564  9877  1736  9848  1908  9816
2079   9781  2250  9744  2419  9703  2588  9659  2756  9613  2924  9563
3090   9511  3256  9455  3420  9397  3584  9336  3746  9272  3907  9205
4067   9135  4226  9063  4384  8988  4540  8910  4695  8829  4848  8746
5000   8660  5150  8572  5299  8480  5446  8387  5592  8290  5736  8192
5878   8090  6018  7986  6157  7888  6293  7771  6428  7660  6561  7547
6691   7431  6820  7314  6947  7193  7071  7071
**********************************************************************
 301   ASSIGN      4     V46               302
 302   ASSIGN      5     FN4               303
 303   ASSIGN      7     FN5               305
 305   ADVANCE                       BOTH  310   315
 310   COMPARE     V47   L     V49         311                    IS THE VEHICLE
*                                                                 STABLE
 311   ASSIGN      8+    K1                312
 312   SAVEX       5     P8                390
 315   LOGIC       R2                      390
 390   RELEASE     3                       600
**********************************************************************
**********************************************************************
**********************************************************************
 400   SEIZE       4                       405                    FACTOR FAMILY
*THREE, THIS FACTOR FAMILY IS THE VEGETATION OF THE AREA
**********************************************************************
 50    VARIABLE    V7*V4                                          VEH. AREA
 40    VARIABLE    V50*FN9+V50*FN10+V50*FN11
```

```
 42   VARIABLE     V40/K129600
**********************************************************************
 405  ASSIGN      5      K3                     410
 410  ADVANCE                            BOTH   411    420
 411  COMPARE     V42    L      V41             412
 412  ASSIGN      8+     K1                     413
 413  SAVEX       8      P8                     490
 420  LOOP        5                             410    425
*THE VEHICLE IS CONSIDERED TO HAVE THREE  CHANCES TO ATTEMPT PASSAGE  OF
*VEGETATION TYPE OBSTACLES.  THIS WOULD BE THE MANEUVERING OF THE DRIVER
*AS HE ATTEMPTS TO BACK AND TURN AROUND THE OBSTACLE.
 425  LOGIC       S3                            490
 490  RELEASE     4                             605
**********************************************************************
**********************************************************************
**********************************************************************
 500  SEIZE       5                             501                 FACTOR FAMILY4
**********************************************************************
 501  ADVANCE                            .001   504    505
 505  ADVANCE                            BOTH   506    525
 506  COMPARE     V10    LE     FN15            507                 BREAK ANGLE
 507  ADVANCE                            BOTH   508    530
 508  COMPARE     V8     GE     FN16            509                 APPROACH
 509  ADVANCE                            BOTH   510    535
 510  COMPARE     V6     G      FN17            511                 WATER DEPTH
 511  ADVANCE                            BOTH   512    540
 512  COMPARE     V32    G      FN18            555                 STEP HEIGHT
 32   VARIABLE    V3/K2                                             WHEEL RADIUS
**********************************************************************
 504  ADVANCE                                   550
 525  ASSIGN      4      K1                     545
 530  ASSIGN      4      K2                     545
 535  ASSIGN      4      K3                     545
 540  ASSIGN      4      K4                     545
 545  SAVEX       21     P4                     560
 560  LOGIC       S4                            590
 550  ASSIGN      8+     K1                     555
 555  SAVEX       20     P8                     590
 590  RELEASE     5                             605
**********************************************************************
**********************************************************************
**********************************************************************
 600  ASSEMBLE    2                             610
 605  ASSEMBLE    2                             610
 610  ASSEMBLE    2                             611
 611  ADVANCE                            BOTH   612    620
 612  GATE        LS1                           613
 613  ADVANCE                            BOTH   614    620
 614  GATE        LS2                           615
 615  ADVANCE                            BOTH   616    620
 616  GATE        LS3                           617
 617  ADVANCE                            BOTH   618    620
 618  GATE        LS4                           650    620
 620  ADVANCE                                   700
 650  LOOP        3                             182    700
**********************************************************************
**********************************************************************
```

```
*****************************************************************************************
700  PRINT       5     5              701
701  PRINT       [illegible]     8              702
702  PRINT       20    20             703
703  PRINT       21    21             704
704  SAVEX       15    V31            705
705  PRINT       10    10             706
706  PRINT       15    15             710
710  RELEASE     1                    750          1
750  TERMINATE   [illegible]
     START       25

SAVEX  NR,      VALUE     NR,     VALUE     NR,     VALUE     NR,     VALUE
        5        337       6         0       7         0       8       [illegible]

SAVEX  NR,      VALUE     NR,     VALUE     NR,     VALUE     NR,     VALUE
        8        337       9         0      10       337      11       [illegible]

SAVEX  NR,      VALUE     NR,     VALUE     NR,     VALUE     NR,     VALUE
       20        337      21         0      22         0      23       [illegible]

SAVEX  NR,      VALUE     NR,     VALUE     NR,     VALUE     NR,     VALUE

SAVEX  NR,      VALUE     NR,     VALUE     NR,     VALUE     NR,     VALUE
       10        337      11         0      12         0      13         0

SAVEX  NR,      VALUE     NR,     VALUE     NR,     VALUE     NR,     VALUE
       15        336      16         0      17         0      18         0

SAVEX  NR,      VALUE     NR,     VALUE     NR,     VALUE     NR,     VALUE
        5        337       6         0       7         0       8       [illegible]

SAVEX  NR,      VALUE     NR,     VALUE     NR,     VALUE     NR,     VALUE
        8        337       9         0      10       337      11       [illegible]

SAVEX  NR,      VALUE     NR,     VALUE     NR,     VALUE     NR,     VALUE
       20        337      21         0      22         0      23

SAVEX  NR,      VALUE     NR,     VALUE     NR,     VALUE     NR,     VALUE

SAVEX  NR,      VALUE     NR,     VALUE     NR,     VALUE     NR,     VALUE
       10        337      11         0      12         0      13         0

SAVEX  NR,      VALUE     NR,     VALUE     NR,     VALUE     NR,     VALUE
       15        336      16         0      17         0      18         0

SAVEX  NR,      VALUE     NR,     VALUE     NR,     VALUE     NR,     VALUE
        5        337       6         0       7         0       8       337

SAVEX  NR,      VALUE     NR,     VALUE     NR,     VALUE     NR,     VALUE
        8        337       9         0      10       337      11       [illegible]

SAVEX  NR,      VALUE     NR,     VALUE     NR,     VALUE     NR,     VALUE
       20        337      21         0      22         0      23         0

SAVEX  NR,      VALUE     NR,     VALUE     NR,     VALUE     NR,     VALUE
```

APPENDIX C

RESULTS OF EXPERIMENTS

Results of Experiment 1

18.1 x 26 Tire Size

Vehicle Number	Area 1 Dist.*	Area 1 Halted by	Area 2 Dist.*	Area 2 Halted by	Area 3 Dist.*	Area 3 Halted by	Area 4 Dist.*	Area 4 Halted by	Area 5 Dist.*	Area 5 Halted by
1										
2										
3										
4			205	4/2						
5	285	4/1			285	4/4				
6					72	4/1				
7			5	4/1						
8										
9					18	4/1				
10					264	4/1				
11	152	4/1			196	4/4				
12	184	4/1								
13										
14										
15	225	4/4								
16	82	4/1	166	4/1			233	4/1		
17										

*Unless indicated otherwise, distance is 337.

18.1 x 36 Tire Size (Continued)

Vehicle Number	Area 1 Dist.*	Area 1 Halted	Area 2 Dist.*	Area 2 Halted	Area 3 Dist.*	Area 3 Halted	Area 4 Dist.*	Area 4 Halted	Area 5 Dist.*	Area 5 Halted
18			19	4/2	43	4/4	80	4/1		
19	231	4/4	111	4/1						
20										
21	188	4/1			7	4/4				
22										
23	62	4/1			287	4/1	123	4/1		
24										
25	82	4/4	212	4/1						

23.4 x 34 Tire Size

Vehicle Number	Area 1 Dist.*	Area 1 Halted	Area 2 Dist.*	Area 2 Halted	Area 3 Dist.*	Area 3 Halted	Area 4 Dist.*	Area 4 Halted	Area 5 Dist.*	Area 5 Halted
1										
2										
3										
4										
5	285	4/1								
6										
7										
8										
9										

23.4 x 34 Tire Size (Continued)

Vehicle Number	Area 1		Area 2		Area 3		Area 4		Area 5	
	Dist.*	Halted by	Dist.*	Halted by	Dist.*	Halted by	Dist.*	Halted by	Dist.*	Halted by
10										
11	152	4/1			23	4/1				
12					292	4/4				
13										
14	255	4/1								
15										
16					28	4/4				
17										
18			292	4/1						
19	222	4/1								
20										
21			85	4/1	316	4/4				
22										
23										
24										
25										

Results of Experiment 2

18.1 x 26 Tire Size

Vehicle Number	Area 1		Area 2		Area 3		Area 4		Area 5	
	Dist.*	Halted by	Dist.*	Halted by	Dist.*	Halted by	Dist.*	Halted by	Dist.*	Halted by
1			0	3	4				7	3
2			5	3	4				18	3
3			2	3	3				4	3
4			13	3	7				6	3
5	285	4/1	6	3	9				3	3
6			5	3	10				4	3
7			15	3	15				5	3
8			27	3	4				4	3
9			4	3	4				8	3
10			4	3	1				8	3
11	152	4/1	4	3	9				2	3
12			2	1	2				14	3
13			3	3	5				4	3
14	255	4/1	2	3	6				4	3
15			2	3	1				2	3
16			23	3	15		233	4/4	15	3
17			2	3	3		80	4/4	6	3

18.1 x 26 Tire Size (Continued)

Vehicle Number	Area 1 Dist.*	Area 1 Halted by	Area 2 Dist.*	Area 2 Halted by	Area 3 Dist.*	Area 3 Halted by	Area 4 Dist.*	Area 4 Halted by	Area 5 Dist.*	Area 5 Halted by
18			21	3	3				6	3
19	222	4/1	7	3	3				2	3
20			24	3	2				2	3
21			18	3	3				11	3
22			3	3	4				4	3
23			10	3	13				2	3
24			7	3	4		123	4/4	9	3
25			8	3	3				4	3

23.4 x 34 Tire Size

Vehicle Number	Area 1 Dist.*	Area 1 Halted by	Area 2 Dist.*	Area 2 Halted by	Area 3 Dist.*	Area 3 Halted by	Area 4 Dist.*	Area 4 Halted by	Area 5 Dist.*	Area 5 Halted by
1			0	3	4	3			5	3
2			5	3	4	3			2	3
3			2	3	3	3			2	3
4			13	3	7	3			2	3
5	285	4/1	6	3	9	3			11	3
6			5	3	10	3			2	3
7			15	3	15	3			4	3
8			27	3	4	3			10	3
9			4	3	4	3			10	3

23.4 x 34 Tire Size (Continued)

Vehicle Number	Area 1 Dist.*	Area 1 Halted by	Area 2 Dist.*	Area 2 Halted by	Area 3 Dist.*	Area 3 Halted by	Area 4 Dist.*	Area 4 Halted by	Area 5 Dist.*	Area 5 Halted by
10			4	3	0	3			24	3
11	152	4/1	4	3	9	3			2	3
12			2	1	2	3			8	3
13			3	3	5	3			5	3
14	255	4/1	2	3	6	3			0	3
15			2	3	0	3			3	3
16			23	3	15	3	233	4/4	9	3
17			2	3	2	3	80	4/4	22	3
18			21	3	3	3			7	3
19	222	4/1	7	3	2	3			8	3
20			24	3	3	3			4	3
21			18	3	4	3			0	3
22			3	3	13	3			4	3
23			10	3	4	3			8	3
24			7	3	3	3	273	4/4	2	3
25			8	3	3	3			14	3

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